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DISSOLVED AIR FLOTATION FOR PRIMARY AND SECONDARY CLARIFICATION

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ABSTRACT

A literature survey of over 60 references on the use of dissolved air flotation (DAF) in water and wastewater treatment revealed that, except for flotation thickening, very little information was available on DAF as an alternative to sedimentation.

In this study, bench-scale batch and pilot-scale continuous flow dissolved air flotation units were used to clarify raw sewage and mixed liquor from an extended aeration and a conventionally loaded activated sludge plant. Performance parameters, such as effluent and float suspended solids, air to solids ratio, and a "thickening parameter", of the batch and continuous flow units were compared for scale-up purposes. Comparisons were also made between the performances of the DAF unit when clarifying the three types of feed.

The research indicated that batch flotation tests were valuable in predicting full-scale DAF performance. The pilot studies showed that the solids in raw sewage and in the mixed liquor from extended aeration or conventional activated sludge plants could be separated by DAF with efficiencies comparable to those reported for sedimentation.

Design criteria for DAF units for each of the three feeds were developed and the costs of utilizing DAF for primary and secondary clarification in municipal plants of 4 500, 45 000 and 227 000 m^3/d capacity were estimated. From an economic point of view, it was found that DAF was not competitive with sedimentation and should only be considered when space is at a premium, land costs are high or when bulking sludges necessitate its use.

RÉSUMÉ

Une étude bibliographique de plus de 60 références sur la flottation sous pression pour le traitement de l'eau et des eaux usées a révélé que, sauf pour l'épaississement par flottation, on possédait très peu de renseignements sur la flottation sous pression comme moyen de rechange à la décantation.

Dans l'étude qui a été réalisée par la suite, des dispositifs de flottation sous pression, de laboratoire, fonctionnant en discontinu, et à l'échelle-pilote fonctionnait en continu, ont servi à clarifier l'effluent brut et la liqueur mixte d'une unité d'aération prolongée et d'une usine d'épuration par boues activées fonctionnant sous des charges ordinaires. On a comparé à des fins d'extropolation les paramètres de fonctionnement (tels que la teneur en matières en suspension dans l'effluent et le floc, le rapport air/matières solides et un paramètre d'épaississement) des dispositifs fonctionnant en continu et en discontinu. On a aussi comparé le fonctionnement de la flottation sous pression lors de la clarification des trois types d'effluents.

Les tests en discontinu ont permis de prévoir le comportement de la flottation sous pression à l'échelle. Les études en unité-pilote ont montré que les matières solides, dans les eaux brutes et dans la liqueur mixte, peuvent être séparées par flottation sous pression, selon un taux comparable à celui de la décantation.

On a élaboré les critères du calcul des unités de flottation sous pression pour chacun des trois effluents traités et on a estimé les coûts de la décantation primaire et secondaire dans des usines municipales de 4 500, 45 000 et 227 000 m^3/j par flottation sous pression. Du point de vue économique, la flottation sous pression ne peut concurrencer la décantation conventionnelle et ne devrait être envisagée que lorsque l'espace coûte très cher, que les coûts du terrain sont élevées ou que le foisonnement des boues l'exige.

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SUMMARY

The work carried out and the results which led to the general conclusions are outlined below.

1) Work by Others. In North America the research and application of DAF in the municipal waste treatment field has dealt, almost exclusively, with flotation thickening of waste activated sludge. Only one case of using flotation for final clarification has been reported. However, several reports on the flotation of raw sewage have indicated favourable results.

   In the United Kingdom, in addition to the flotation thickening of waste activated sludge, considerable research and several field installations have indicated success in clarifying raw water. Microflotation and electroflotation are the two concepts receiving the most attention in continental Europe, where interest has centred on water treatment or industrial use.

   The application of DAF as an alternative to sedimentation has reached an advanced stage in South Africa, where tenders have been called for DAF units in place of final clarification in a 150 000 m^3/d plant.

   Manufacturers producing the standard DAF units in North America include Komline-Sanderson, Eimco-Envirotech, and Rexnord. Manufacturers offering unusual designs include: ICI (CIL in Canada), which promotes the deep shaft process (microflotation); Ingersoll Rand, with a counter-current flow unit; and Permutit, which offers a lamellar design. Each of these unique methods is recommended for specific situations.

2) Bench Scale Test. A three-cylinder bench scale DAF unit was developed based on a design reported by Wood in 1970. The unit used in the present study incorporated a dissolved oxygen meter which indicated air concentrations under high pressures. Operation was simple, and the apparatus enabled pre-selection of wastewater treatment chemicals and realistic, operating performance parameters for the pilot unit.

3) Process Scale-Up. A comparison between the bench (batch) and pilot (continuous flow) tests for the three phases of the study indicated similar values for the air to solids ratio, polymer dose and float concentration. However, in all three cases, a better effluent was obtained from the continuous flow pilot plant. Despite opinions that pressure affects flotation performance, batch tests showed no discernible measurable effects, and the influence of different pressures between the bench and

pilot-scale units could be accounted for in the analysis of the performance parameters used (See 5) below). Therefore, no scale-up factor was required with the use of these parameters.

4) Flotation Additives. Twenty-five polymers from three manufacturers were tested in the bench scale unit and the most suitable one, on the basis of performance and cost, was selected for each phase of the project. The impact of three phosphorus removal chemicals (lime, alum and ferric chloride) was assessed on the bench-scale unit. No significant deterioration in flotation performance was observed; in fact, flotation was improved by ferric chloride addition in the conventional activated sludge process.

5) Process Evaluation. The usual parameters for evaluating flotation performance, i.e., float or effluent solids concentration, and air to solids ratio were found to be in many cases unrelated to each other. A "thickening parameter" or "thickening equation" was developed that provided a better measure of thickening performance because influent and float solids concentration and the air required could be considered. These two parameters are also useful for predicting the air requirements in full scale operation.

6) Operational Problems. The heart of a DAF unit is the air dissolution system. The functioning of this system is most critical to plant performance, and requires vigilant attention. All other mechanical equipment (pumps, mixers, skimmers, etc.) needed regular maintenance, but provided this was done, these components could be relied upon at all times. The air eductors were extremely susceptible to clogging, and the level control system in the pressure tank would malfunction when the effluent quality (and hence recycle quality) began to deteriorate. This problem was most severe in phase 1 (extended aeration) and phase 3 (conventional activated sludge) because of the flocculant nature of the incoming sludge. In contrast, the raw sewage of phase 2 created less severe problems, and the system could operate for many hours with a poor effluent. Hence, contrary to expectation, plant reliability was best when raw sewage was used.

Plant operation was simpler with raw sewage for another reason: it was demonstrated that polymer addition was preferable, but not essential; the plant could function adequately without polymer, albeit with a more erratic effluent quality. Therefore, in phase 2 the plant was not totally dependent on the supply of polymer, whereas in phases 1 and 3, polymer addition was necessary.

Finally, because of the very low loading of solids in phase 2, float build-up was negligible, and carry-over of float into the effluent did not occur. The skimming cycle could not be adjusted in such a way that a float blanket could build up because of foaming problems. This shallow float depth did not result in a poor float solids concentration, although there was negligible time for thickening.

In summary, the simplest and most reliable operation was achieved with raw sewage feed.

7) Estimated Costs. Using flotation as an alternative to sedimentation for the separation of solids in raw sewage or mixed liquor increases capital costs by 1.5 to four times and operating costs five to 20 times, depending upon the application and the size of plant. The use of flotation in place of sedimentation can only be justified for municipal waste treatment when land costs are high or limited space is available.

8) Process Modifications. Several modifications to the Komline-Sanderson unit were made to improve its operation. Plugging of the air dissolution system was controlled by incorporating a backwash connection to the recirculation system, thus enabling the eductor to be cleaned out while the DAF unit was still operating. The insertion of a dissolved oxygen probe (of a type able to monitor oxygen under high pressure) in a by-pass line permitted accurate determination of the available air. Because of the build-up of floated sludge at high solids loading, the sludge scraping operation had to be improved. This was accomplished by the addition of a baffle and a beeching plate.

Modifications such as the addition of patented air dissolution systems, inclined plates, tubes, etc., were not considered for the Komline-Sanderson unit. The unique features of other manufacturers' equipment incorporating some of these ideas are noted in the text.

Conclusions

It has been determined that DAF is a feasible alternative to gravity settling in municipal wastewater treatment in terms of sludge concentration and effluent quality. However, both capital and operating costs for DAF are considerably higher than those for equivalent performance using sedimentation followed by flotation thickening where necessary.

When used for the clarification of raw sewage, DAF produced a sludge concentration of approximately six percent and effluent suspended solids of 40 mg/L. These values are comparable to those obtainable using sedimentation, providing waste treatment chemicals are added in both cases. Although the hydraulic load for flotation is about eight times that for sedimentation, both capital and operating costs are approximately three to five times greater for DAF than for sedimentation (neglecting land costs), depending upon the size of the plant.

Clarification of mixed liquor from an extended aeration plant by flotation produces effluent quality of about 15 mg/L, similar to that obtained from sedimentation. However, the DAF float of about four percent is perhaps four times that from a final settling tank. To compare costs on an equitable basis, flotation thickening would have to follow gravity settling. Hydraulic loading for flotation would be roughly four times that of sedimentation but the capital costs would be two to three times, and the operating costs up to 18 times the costs for sedimentation with flotation thickening.

Clarification of mixed liquor from a conventional activated sludge plant also produced sludge and effluent solids concentrations comparable to those obtainable from gravity settling followed by flotation thickening, i.e., 7.5 percent and 20 mg/L, respectively. Hydraulic loads for flotation can be six times those for sedimentation, but again the cost comparison favours sedimentation. The ratio of capital cost is 2:1 and operating cost as high as 20:1 for a 227 300 m^3/d plant.

Recommendations

This study showed that flotation is a technically feasible alternative to sedimentation of municipal wastes, but is difficult to justify economically. It is recommended that consideration be given to DAF only when land costs are high or when sludges resist gravity settling. The process seems promising for plants that experience periodic or continuous sludge bulking. It has been postulated that the degradation of substrate by filamentous microorganisms is more rapid than that by more commonly encountered "zoogleal" microorganisms. However, filamentous microorganisms are notoriously difficult to compact, and are responsible for many cases of sludge bulking. Wastes of high carbohydrate content (e.g., brewery, dairy) are particularly prone to this condition, and studies of separation by flotation on such sludges, possibly in combination with municipal sludges, should be pursued.

1 INTRODUCTION

The separation of solid and liquid phases is a critical part of all waste and water treatment operations. Gravity sedimentation has traditionally been the most popular method; however flotation, or the reverse of settling, is being increasingly applied for clarification purposes.

Flotation will occur naturally in a solid/liquid suspension if the solid fraction has a density lower than that of the liquid. When this is not the case, flotation is induced by the creation of an air/solid agglomerate whose combined density is less than the liquid density. The air bubbles may be created by a number of processes, such as electrolysis, photosynthesis, physical agitation, and by changing the pressure of an air-saturated liquid. This last effect may be achieved by imposing vacuum conditions on the liquid initially at atmospheric pressure, or by releasing a previously applied pressure. The latter method, referred to as dissolved air pressure flotation, hereinafter more conveniently as DAF, is the one most commonly used in the sanitary engineering field, and is the basis of this study.

DAF has, over the past 20 years, been applied most often to the thickening of activated sludge. Since the upward or buoyancy force can be controlled and made larger than gravity, it is possible to thicken larger quantities of sludge by flotation than by gravity thickening, in the same time. This advantage, in turn, leads to space savings and in some cases reduced capital costs. Furthermore, a more concentrated thickened sludge can be obtained by flotation than by gravity thickening.

Apart from its application to activated sludge thickening, DAF has been used in virtually all other situations requiring clarification, including raw water treatment, raw sewage treatment, effluent polishing, primary sludge plus activated sludge thickening, and clarification of mixed liquor. The paucity of information regarding the use of DAF in clarifying activated sludge mixed liquor, especially in the field of domestic sewage treatment, prompted this research.

2 OBJECTIVES AND LIMITATIONS OF THE STUDY

The primary objective of the study was to examine the feasibility of using DAF as an alternative to gravity settling in municipal wastewater treatment. Screened raw municipal sewage and mixed liquor from activated sludge plants operating at two different food to microorganism (F/M) loadings were the wastes to be considered. The achievement of the following secondary objectives was a necessary part of the examination and would provide useful information on the application of DAF in specific situations:

1) an assessment of the work done by other researchers and by manufacturers of DAF equipment;
2) the development of a useful bench scale test for evaluating DAF process performance;
3) the operation of a pilot scale DAF unit in parallel with the bench tests in order to develop methodology for process scale-up;
4) examination of the effect of flotation aids and phosphorus removal chemicals on DAF, with the optimum condition to be determined from bench tests and applied at pilot scale;
5) process evaluation based on solids and hydraulic loading, air to solids ratio and other parameters applicable to process performance and design;
6) the recording, and where possible, the correction of DAF operational problems encountered during the investigation;
7) estimates of the capital and operating costs for DAF units of various sizes and comparison with the comparable costs for gravity settling;
8) consideration of potential process modifications as suggested by the investigation and from discussions with DAF manufacturers.

Some limitations inherent in the investigation should be mentioned. Because the municipal wastes (with varying solids concentrations) were tested at constant inflow rates, the effects of shock hydraulic loads or of fluctuating flows on the process were not evaluated. Also, since only a limited number of polymers and chemicals could be tested and only one type of DAF unit was employed, the results should be used with discretion in cases where actual conditions are different than those during this study. Finally, the source of sewage for all three phases (i.e., sewage fed to the activated sludge plant for phases 1 and 3, and that fed directly to the DAF unit in phase 2) was the Burlington Skyway Sewage Treatment Plant. This plant treats predominantly domestic sewage from

a population of 75 000. The results of this study may not, therefore, be applicable to wastewaters that are not similar to the screened raw sewage from Burlington.

3 LITERATURE SURVEY AND REVIEW OF AVAILABLE EQUIPMENT

3.1 Introduction

The "flotation" process was transferred into the field of waste and water treatment from the mining, metallurgical and chemical industries, where it is used to separate solids from liquids, and solids from other solids. Flotation is now a widely used treatment method in waste and water purification. The present study was concerned with a portion of this rapidly expanding field, that of the application of dissolved air pressure flotation treatment to the clarification and thickening of raw sewage and mixed liquor from various types of activated sludge processes. This literature survey concentrates on the literature pertinent to the field of study, but for the sake of completeness, the wide variations of the basic processes applied in the waste and water treatment fields are also outlined.

In 1952, Laboon reported on the concentration of raw sludge and activated sludge by flotation caused by the evolution of gas under anaerobic conditions. This was aided only by temperature and time controls. Novel applications of dispersed air flotation have been reported by van Vuuren et al. (1968) and Stander and van Vuuren (1970). Humus tank effluents were treated in the former study, and the air for flotation was supplied via venturi pipe to the suction line of the feed pump. The second study utilized the supersaturated oxygen conditions produced in maturation ponds (with algal activity) to effect flotation.

The electroflotation process, in which gas bubbles are produced by electrolytic means, has been used periodically in the field of water and sewage treatment. Sandbank et al. (1974) reported the application of this method for treating raw sewage by mixing it with seawater and passing the mixture through an electrolytic cell. Magnesium hydroxide from the seawater was useful for flocculation. A paper by Barrett (1975) concerns further application of the electroflotation process in cases where the high cost of power and electrode replacement is justified. Chambers and Cottrell (1976) reported on the use of improved electrodes in treating relatively low flows (20 m^3/h) of certain industrial wastes by electroflotation.

The microflotation process was developed in Sweden for the treatment of domestic and industrial wastes (Hemming et al., 1976). In this process, air is dissolved by hydrostatic pressure at the base of a deep shaft (typically 10 m), and flotation occurs in an overflow tank at the top of the shaft.

In all the variations referred to above, air is made available to induce flotation. Vacuum flotation, in which air is released when the influent is subjected to a pressure below atmospheric, is another basic method. It has not, however, found wide application in waste and water treatment (Chase, 1958; Dick, 1972; Eliassen and Schulhoff, 1944) because of the limited amount of air that can be made available for flotation and due to practical difficulties. Dissolved air pressure flotation is the system most commonly applied, and this method can be further subdivided into full-pressurization, partial pressurization, and recirculation systems. The recirculation method is most popular for sludge thickening, and a review of this process, as practised widely in the U.S.A., is given by Komline (1976).

3.2 Brief History

Flotation as a unit operation found application initially in the mining and metallurgical industries, and the first patent for mineral flotation was taken out by William Haynes in 1860 (Hansen and Gotaas, 1943). Elmore was responsible for the original work in vacuum flotation in the early 1900's, but the first successful unit has been attributed to Clemens. The Juell pressure flotation machine was the first unit of its kind (Vrablik, 1959).

The first appearance of flotation in the waste treatment field occurred in the paper industry. In Scandinavia during the 1920's, the "Savealls" process using vacuum flotation was developed to recover fibres from paper mill wastes. The first application of flotation to sewage treatment was at a California plant in 1942, and primary treatment of sewage by vacuum flotation is reported for a plant in Oklahoma in 1951. For a review of flotation applications up to 1957, see Chase (1958).

The first full-scale DAF installation for clarifying and thickening mixed liquor from a domestic activated sludge plant is attributed to a 3 800 m^3/d works in Prince William County, Virginia (Mulbarger and Huffman, 1970).

3.3 Theory

The basic theories of flotation and discussions of the conventional processes are presented in basic texts on sanitary engineering unit operations by Rich (1961), and Dick (1972), in numerous review papers, e.g., Vrablik (1959) and Turner (1975), and also in the appropriate section of the U.S. Environmental Protection Agency (EPA) design manual on sludge treatment (1974).

Vrablik's classic paper (1959) contains most of the theory basic to DAF. The fundamental principles are laid out, and the notion advanced that flotation performance is based on the surface properties of the sludge. The mathematical theory presented is essentially that of classical sedimentation in reverse, and includes the Reynolds' number and use of Stokes' law. Ettelt (1964) carried this exercise further, and uses the dimensionless air to solids number (A/S) in many equations and graphs concerning the flotation of discrete particles. The problem is that none of these basic theories apply for flocculent sewage suspensions.

Howe (1958) refers to various theories explaining the nature of the flotation process: electrical, contact angle, gas, and absorption theories. His mathematical approach follows lines similar to that of the previously mentioned researchers, but includes parameters such as liquid and solid densities and viscosity. An exponential equation is derived that relates the fraction of solids removed to the independent variables. Mulbarger and Huffman (1970) expanded this work and included the A/S ratio in the exponential equation. They then applied the equation successfully to the results from full-scale experiments.

Apart from mathematical and related theories concerned with prediction and design, explanations as to why the system behaves as it does have been considered by many investigators. Vrablik (1959) presents three possible mechanisms by which flotation may result after bubble formation:

1) Adhesion of a gas bubble to a suspended liquor or solid phase.
2) The trapping of gas bubbles in a floc structure as the gas bubble rises.
3) The absorption of a gas bubble in a floc structure as the floc is formed.

Baum and Hurst (1953) compared bubble formation and attachment in dispersed air and dissolved air flotation systems. With dispersed air, a mixture of bubbles and solids exists in the liquid phase, and it is necessary to attach the bubbles to the solid. In dissolved air flotation (DAF), the air bubbles use the solid particles as the nucleus for bubble formation; hence the flocculation or collecting stage of the process is eliminated, and smaller quantities of chemicals are required to effect adequate performance.

The size of the air bubbles also has a significant effect on flotation. Vrablik (1957) explained that air bubbles should be as small as possible because, the smaller the bubble, the larger the contact angle and the greater the unit surface area covered per unit bubble surface area. The contact strength between the two will in turn be increased. Kormanik (1974) made the controversial claim that the optimum bubble size is produced

at a pressure of 280 kPa, but Bratby and Marais (1975) asserted that, from an economical standpoint, the optimum saturator pressure should be 350 kPa. At pressures lower than this, it was difficult to attain a high level of saturation.

The use of chemicals to improve flotation performance is common. Virtually all full-scale plants use one or more forms of flotation aid. As early as 1943, Hansen and Gotaas experimented with heterpolar organic compounds to change the surface tension and the contact angle. Vrablik (1959) referred to seven types of chemicals used to assist flotation: flocculators, frothers, promoters, depressants, activators, sulphadizers, and pH regulators. In the wastewater treatment field, flocculators are used almost exclusively, and these are usually polymers and/or chemicals such as alum or ferric chloride (McMichael, 1974; Komline, 1976; Levy et al, 1972).

Most operating full-scale DAF units in North America use pressurized recycle to supply air. The reasons are:

a) pressurizing equipment is easily clogged by untreated liquors;
b) pressurizing the sludge tends to cause floc break-up; and
c) the quantity of air available for flotation can readily be varied over a wide range, depending on the recirculation ratio.

For further discussion of this factor, see Dick (1972), Eckenfelder et al. (1958), Komline (1976), Vrablik (1959), and Wood and Dick (1973).

3.4 Laboratory Studies

In their 1953 paper, Kalinske and Evans pointed out that an important feature of the DAF process is the sudden release of the pressurized waste or recycle through a pressure release valve. If the liquid is pressurized and the pressure then gradually released, the air bubbles will not come out of solution, and the liquid will remain supersaturated. In practice, the rapid drop in pressure occurs when the pressurized liquid passes from the pressure vessel to another vessel at atmospheric pressure; the turbulence created causes bubble formation and release.

Eckenfelder et al. (1958) pioneered laboratory investigations of DAF. They used the now familiar two-cylinder or "bomb" test, which is detailed in the 1958 article and in an article by Eckenfelder and Ford (1970). The importance of the A/S ratio was stressed, and other parameters such as sludge type and sludge volume index (SVI) were assessed for their effect on float and effluent concentration. The presentation had a major shortcoming in that no consideration was made of variable influent solids

concentration; it was presupposed that this and other parameters such as SVI and temperature were constant for a wide range of tests. Also, the percent saturation was assumed to be either 100 percent or was left unmentioned. It should be noted, however, that these shortcomings were present in most of the flotation studies reviewed.

The article by Eckenfelder and Ford (1970) is widely used as a "manual" for conducting laboratory studies of DAF. The principal components used in DAF are a pressurizing pump, a cylinder serving as a retention tank, a connector and pressure reducing valve, and the cylinder serving as the flotation tank itself. The authors outlined the standard laboratory procedure simply, but a more recent article by Turner (1975) provides more detail on this particular laboratory approach.

Stander and van Vuuren (1970) list some of the important criteria that should be evaluated in the laboratory:

1) most suitable flocculent, and optimum dosage and mixing requirements;
2) period required for floc formation and conditioning;
3) aeration requirements;
4) rate of separation of the aerated suspended solids (rise rate);
5) necessity, and if required, dosage, of a suitable activator to improve adhesion of the gas bubbles.

Wood and Dick (1973) added to this list:

6) Will the material actually float?
7) How well will the material float?
8) What degree of effluent clarification can be expected?

In their 1973 paper, Wood and Dick reported on a significant advance in the laboratory technique. An apparatus with three cylinders instead of two was used, and judged superior and more representative of full-scale units than the "bomb" apparatus. Continuous blending of the waste (influent) and pressurized recycle streams was considered to approximate more closely the operation of continuous units. Higher rise-rates were obtained and more complete flotation (i.e., smaller quantity of solids in the subnatant) of the solids occurred when the three-cylinder apparatus was used than with the two-cylinder unit.

Mennell et al. (1974) investigated the clarification of primary effluent by lime addition followed by DAF. They used a continuous flow bench-scale plant requiring 1 L/min feed in a countercurrent mode of operation. An air disengaging section was used

at the bottom of the flotation column to facilitate bubble production and efficient adhesion, and high precision pumping and measuring equipment was used.

Wood and Dick (1974) expanded on the information in their previous article by considering the effects of sludge characteristics on flotation behaviour. The two parameters used to describe the sludge were yield strength and plastic viscosity, measured by a coaxial cylinder rotational viscometer. While these parameters gave quantitative measurements of the sludge characteristics, they could also be related qualitatively to the type of filamentous organisms present. It was found that as the yield strength and the plastic viscosity increased (implying an increase in the number of filamentous organisms) the float concentration decreased. A recommendation was made that those wastes which settle poorly (due to the presence of filamentous organisms) should be separated by flotation, and that the filamentous organisms, which are often more efficient in the degradation of substrate, be utilized in the treatment process, rather than be destroyed by chemical or other means. (See also Wood, 1970.)

Speece et al. (1975) patented an ingenious low-energy gas transfer system, described in detail in their paper. The Wood and Dick apparatus described above was used in their laboratory investigations. The authors stated that the volume of gas given off after depressurization was measured in a closed system, but did not give details about the procedure. Saturation of 75 percent was supposedly achieved.

The Water Research Centre in England has done a considerable amount of research into the use of DAF for treating a wide variety of surface waters. Their flotation program required the design of a flotation jar-test apparatus in order to study a range of variables in the laboratory. The equipment and experimental procedure is summarized by Hyde et al. (1977). Three flotation vessels of 1.2 L capacity were provided with variable-speed drive paddles. A manifold connected to the base of the jars supplied, via solenoid valves activated by timers, a flow of water that had been saturated with air at pressures up to 690 kPa. The controls enabled the same or different discharges of dissolved air to be made to each vessel.

The level of air saturation in the DAF system is critical to performance. Eckenfelder et al. (1958), among others, commented on the variation of this factor under various physical conditions. Methods for measuring the saturation percentage have been presented by Leininger and Wall (1974), Bratby and Marais (1975), and Gehr and Henry (1976), but this value is usually assumed by researchers to be anywhere between 75 percent and 100 percent (Dick, 1972; Eckenfelder and Ford, 1970; Vrablik, 1957).

3.5 Pilot Plant Studies

The material in this and the following section is divided into four categories: domestic raw sewage; domestic activated sludge; industrial wastes; and raw water effluent polishing.

3.5.1 Raw Sewage. One of the earliest DAF pilot plant investigations into the treatment of raw sewage was reported by Hay in 1956. Studies were conducted at the Racine Sewage Treatment Plant in Wisconsin, U.S.A. Plant expansion required either construction of new primary treatment facilities, or the conversion of one of the existing sedimentation tanks to a flotation tank. Pilot tests showed that the DAF process was capable of removing greater than 50 percent SS, and that the increased operating costs would be more than offset in this case by the savings in construction costs.

The treatment of raw sewage and combined sewer overflows by DAF is reported by Levy et al. (1972), and White and Cole (1973). The work was carried out at the Baker Street outfall DAF facility in California, U.S.A., an automated 24-mgd (1.05-m^3/s) pilot plant designed to operate only for the overflow from storm peak flows. In conjunction with alum pretreatment of 0.8 to 3.2 mg/g influent total solids (TS), and with an air to solids ratio (A/S) ranging between 0.05 and 0.10, removal in excess of 90 percent of the solids in the influent stream was effected. Polymer addition was found to be unsuitable.

Huether (1974) reported on the primary treatment of raw sewage by DAF. Tests at the Wastewater Technology Centre, Burlington, Ontario, were done using raw sewage from the Burlington Skyway Sewage Treatment Plant. A 15-ft^2 (1.39-m^2) Komline-Sanderson DAF unit was employed to study the effects of A/S, and chemical and polymer addition. Optimum solids removal occurred at an alum dose of 100 mg/L combined with a polymer (Dow A-32; anionic) dose of 1.0 mg/L. The A/S was estimated at between 0.35 and 0.45. Solids reductions above 90 percent from an influent suspended solids (SS) ranging between 220 and 540 mg/L were achieved with a float concentration of between 2.5 and 3.5 percent.

3.5.2 Waste Activated Sludge from Domestic Sources. In a comprehensive paper on the theory and practice of flotation, Ettelt (1964) described laboratory and pilot plant experiments dealing with the thickening of waste activated sludge at the Chicago Southwest plant. A sludge concentration of approximately five percent was required for the self-sustaining operation of the Zimpro process, and for this reason flotation was employed instead of gravity thickening. The experimental unit consisted of a converted

settling tank, 300 m^2 by 4.4 m deep. Parameters optimized included inlet design, type of recycle, A/S, solids loading, and chemical addition. A substantial discussion of operating problems is included.

Brown (1972) described two sets of pilot plant experiments with flotation at the Crossness works in England. A "Simcar Electraflote" plant, which uses gas generated by electrolysis, was tried but rapid deposition of material on the carbon cathode rendered the plant unsuitable. The second set of tests was conducted on a 15-ft^2 (1.39-m^2) Komline-Sanderson DAF unit. The process was regarded as promising for Greater London Council use, although optimum conditions had not yet been found in the tests reported. An original feature of the experiments was the attempt to obtain a thicker sludge by allowing the float to drain on a wire mesh. An increase of sludge solids from four percent to six percent was possible.

The effects of various control variables on flotation performance were reported by Campbell and Le Clair (1974), and Campbell, Tew and Le Clair (1975). The performance of a laboratory-scale batch unit, a Komline-Sanderson 1-ft^2 (0.093-m^2) pilot plant, and a Komline-Sanderson 15-ft^2 (1.39-m^2) pilot plant were compared. Operating results from a 400-ft^2 (37-m^2) full-scale DAF unit at the City of Hamilton's sewage treatment plant were also studied. It was concluded from a limited series of tests, and using assumptions regarding the A/S ratio, that the batch, bench and pilot scale units could be used to design full-scale units with reasonable precision. The second article also included a cost analysis of DAF, as well as some interpretive graphs relating float solids to A/S and to polymer dose.

Davis (1977) reported on the use of DAF at the Olifantsvlei sewage purification works in Johannesburg, South Africa. A 1.39-m^2 Komline-Sanderson unit was used to thicken both mixed liquor and return activated sludge. The Olifantsvlei plant had a solids retention time of 25 days, and this resulted in excellent bio-flocculation which made the sludge particularly amenable to flotation without the use of chemicals or polymers. This study will be discussed further in Section 3.9.

For a summary of operating data from 19 pilot plants in the U.S.A. treating mixed liquor or return sludge, see Environmental Protection Agency (1974).

3.5.3 Industrial Wastes. The use of DAF in the treatment of industrial wastes has been more widespread than in the field of domestic sewage, and a considerable body of literature exists in this area. The following review considers only those articles which, in opinion of the authors, have relevance to the present study.

The use of DAF for the clarification of mixed liquor from an Ontario treatment plant handling nylon manufacturing wastes with bulking tendencies was discussed by Climenhage and Stelzig (1973). A pilot plant for the biological treatment of chemical wastes incorporated a two-stage activated sludge process for nitrification and denitrification. The evolution of nitrogen gas was expected to cause floating problems in the clarifier; furthermore, filamentous bulking (with an SVI higher than 400) caused further operating difficulties with the clarifier, and upset the entire process. It was decided to use a flotation unit in place of the gravity clarifier. Results indicated that the use of DAF would be feasible, and that an effluent solids concentration of from 40 to 80 mg/L was possible without polymer. When 5 mg/L of Rohm and Haas C-3 was added, the effluent SS was reduced to between 10 and 30 mg/L.

Electrolytic and DAF flotation of mixed liquor from an integrated pulp and paper mill at Filer City, Michigan, USA, were investigated (Walzer, 1975). The use of electrolytic flotation was unsuccessful, but the DAF unit proved to be an economical method for mixed liquor clarification. A 51 percent saving in capital cost with DAF over that of a gravity clarifier was calculated, and the fact that no chemicals were required indicated that operating costs would be comparable. The flotation unit used in the study is of special interest. The Permutit Favair Mark II differs from conventional DAF units in that it has longitudinal baffles or "lamels" in the flotation compartment, which reduce the Reynolds' number and, it is claimed, allow the plant to operate at a loading rate two or three times higher than conventional flotation units. Furthermore, pilot plants can use the same basic tank with fewer lamels, eliminating scale-up problems. The authors did not comment on the possible problems arising from the complicated inlet arrangements, and cleaning and maintenance of narrow tank sections.

Valiquette (1976) reported on another industrial application of the lamellae in the flotation tank to improve performance. DAF was tested as a primary treatment method for the woodroom effluent from the Kruger pulp and paper mill in Bromptonville, Quebec. It was found that when lamellae were used, the feed rate could be increased by about 30 percent for the same SS removal efficiency. Parsons (1977) reported the use of the Permutit Favair Mark II DAF unit for clarifying a mixture of activated sludge mixed liquor and final clarifier effluent. The purpose was to determine whether the unit could be successful as an effluent polishing process, and whether it could cope with short-term high solids loadings resulting from temporary clarifier failure. The activated sludge unit itself treated wastewater from a prepared foods plant. The DAF process was found to be

highly effective in reducing excess SS from the clarifier effluent provided polymer was added.

In another recent article, Albert (1977) describes a comparative study of the thickening of industrial and municipal waste activated sludges using plug and counter-current flotation thickeners. The latter, developed by Ingersoll-Rand Company, operate on the principle that the counter-current mode of flow should provide increased opportunity for bubble/solids contact. It was claimed in the article that this counter-current method of flotation thickened two to four times more solids per effective flotation area than conventional plug-flow thickeners with similar float and effluent quality. Furthermore, the required A/S ratio was about 50 percent lower. However, the conclusions were based on an extremely limited set of (presented) data.

3.5.4 Raw Water. As early as 1952, a flotation process for purifying raw water was described by Hopper and McCowen. Although the tests were only done at laboratory scale, the concept and the results have a bearing on full-scale application. The authors used aeration and a surface-active agent to effect flotation, and then analyzed the subnatant for turbidity, toxicity and chemical residual. The removal of bacteria, parasites and viruses was also determined. It was concluded that flotation was an effective water treatment process, but that chlorination would still be required subsequent to flotation in order to render the water fit for consumption.

Zabel et al. (1976) reported on the experimental program at the Water Research Centre in England. This organization has five pilot plants each treating 2300 m^3/d of chemically-flocculated raw water, prior to sand filtration. The waters studied ranged from stored, eutrophic water, to turbid river water. Due to the short period in which the experimental program had been in operation, only limited conclusions could be drawn, but it appears that flotation is a viable alternative to sedimentation for the waters so far investigated.

Hyde (1977), from an extensive bibliography, reviewed the development of flotation for water clarification in Europe and in England. In 1973, there were 71 dissolved air flotation plants in operation for water clarification in the Scandinavian countries. Hyde's article also covers the pilot-plant studies which preceded the commissioning of the five larger DAF units described by Zabel et al. (1976).

Test results from four prototype DAF plants treating aerated pond and/or polishing pond effluents are summarized by Snider (1975). The plants treated rendering,

vegetable canning, poultry plant, and municipal wastes. In all cases, effluent BOD and SS were below 6 mg/L, but alum and polymer treatment was also required.

3.6 Full-Scale Installations

3.6.1 Raw Sewage. A full-scale vacuum-flotation unit operating at the McAlister plant in Oklahoma, U.S.A., was described by Collins and Burns (1951). The BOD of the screened sewage was reduced by 28 percent at an average overflow rate of 194 $m^3/m^2 \cdot d$.

In their 1973 paper, Gupta and Agnew reviewed the operation of two full-scale DAF plants treating combined sewer overflows. The first was in Milwaukee, Wisconsin, U.S.A., and treated a flow of 18 900 m^3/d. Loading was extremely variable because the plant had to handle first-flush flows as well as flows from subsequent storms. Nevertheless, removals of both SS and BOD were around 30 percent at the hydraulic loading of 2.24 $L/m^2 \cdot s$; both chemical ($FeCl_3$, 20 mg/L) and polymer (Dow, C-31, 4 mg/L) were needed.

The second project was based on the design of the first. Two plants in the City of Racine, Wisconsin, U.S.A., treating 53 400 and 168 000 m^3/d were evaluated. Both plants started automatically when the level in the outfall sewer reached a predetermined level. System evaluation was continuing at the time of publication of the paper, and no results were presented.

White and Cole (1973) reported on a 91 000 m^3/d full-scale DAF unit similar to that described above treating combined sewer overflows. This plant is the Baker Street facility in San Francisco. It was found that liquid loading rate, and type and dosage of chemical additive were the two variables which had the greatest effect on DAF performance when A/S was non-limiting. Alum addition at 6.0 mg/L was found to be suitable, and the threshold A/S was 0.02, above which no further improvement in performance occurred. A suitable hydraulic loading rate for the full-scale unit was not given.

3.6.2 Activated Sludge from Domestic Sources. As mentioned previously, Ettelt's article (1964) dealt with flotation units that preceded the Zimpro process. Performance of the full-scale DAF unit was improved by using orifice plates in the feed line from the saturator to contain expansion within the inlet. A further improvement in solids recovery was possible when polymer (in this case Dow Purifloc 601) was added. Two years later, Ettelt and Kennedy (1966) reported further on the operational experience with DAF at the Chicago plant. When 15 percent raw sewage was mixed with 85 percent activated sludge,

the float solids concentration was increased. However, the recycle ratio had to be raised from 250 percent to 300 percent to achieve adequate performance.

Details of existing DAF installations in the U.S.A. were listed in a paper by Katz and Geinopolis (1967). Eight plants not using chemical addition were covered, the majority treating domestic wastes. Four plants were treating combined primary and secondary sludges. Operation and performance data for two plants that used cationic polyelectrolytes were then tabulated, and since both plants also had operating data without polymer addition, a comparison could be made. It was found that float solids concentration was not increased by polymer addition, but that the plants could be fed a higher solids load and solids capture would be increased, leading to a clearer effluent.

Mulbarger and Huffman (1970) described what they claimed was the first full-scale application of DAF for mixed liquor clarification. Their study of the 3800 m^3/d plant in Prince William County, Virginia, U.S.A., involved investigating performance over a wide range of flows and solids concentrations: 2270 - 4540 m^3/d and 960 - 8000 mg/L, respectively. The sludge originating from mechanically-aerated tanks had consistently low SVI of 58 mg/L. The effluent solids quality deteriorated markedly from about 100 to as high as 600 mg/L when the loading exceeded 73 $kg/m^2 \cdot d$. On the other hand, float solids appeared to be more influenced by float detention time than by the solids loading rate. In a cost-quality comparison with sedimentation, flotation was found to produce a poorer effluent, to incur higher power and capital costs, and to be more difficult to operate. The only advantage was that a thicker sludge was produced.

An article by Burfitt (1975) describes the performance of a full-scale DAF unit at the 24 000 m^3/d Aycliffe Sewage Works in England. Using Zetag 94 polymer at 9.5 mg/g, 850 m^3/d of surplus activated sludge containing 5000 mg/L SS could be thickened to 4.5 percent TS with an effluent of 18 mg/L SS. Solids load was 7.8 $kg/m^2 \cdot h$. A more recent paper by Ashman (1976) presented further data on the operation of the Aycliffe DAF plant.

In a comprehensive review, Komline (1976) provides an example to demonstrate how the use of DAF instead of gravity thickening before vacuum filtration will save chemical and labour costs, as well as capital costs, in a combined thickening/filtration system. The author notes that Komline-Sanderson has built over 350 flotation units, the majority of which thicken waste activated sludge. The article includes a summary of the operating data from 20 pilot and full-scale installations in the U.S.A., most of which treat municipal sewage. A detailed cost analysis of flotation thickening for plants of 37 850 and 378 500 m^3/d capacity is also given.

Hemming and Cottrell (1976) reported experiences in Sweden and Finland with the full-scale treatment of domestic sewage by the micro-flotation process. Overall treatment was either physical/chemical, in which case the flotation process was used after chemical coagulation, or biological/physical/chemical, where flotation would be used to clarify mixed liquor.

3.6.3 Industrial Wastes. One of the first applications of flotation in the waste treatment field was for the treatment of wastewaters containing a high proportion of oil and fat. In his 1957 presentation to the Purdue Industrial Waste Conference, Vrablik gave details of a system which employed gravity settling followed by DAF to treat wastewater from the Watson oil refinery in San Francisco. Since particulates would not be a problem, the entire waste was pressurized. At an overflow rate of approximately 4.9 m/h, mineral oil concentration in the influent was reduced from 100-125 mg/L to 30-45 mg/L without the addition of chemicals.

Bridle et al. (1976) reported full-scale operating data on the treatment of high-strength chemical plant wastes (examined at pilot scale by Climenhage and Stelzig (1973) as described in section 3.5.3). A DAF unit was used for the separation of biological solids, in place of a gravity clarifier. Problems were experienced with operation of the flotation unit, especially at high food to microorganism (F/M) ratios, but after various modifications, performance was considered adequate in terms of clarification. The concentration of the float varied between one percent and three percent and that of the effluent SS between 100 and 400 mg/L. No mention of chemical addition was made.

Since November 1974, an Ingersoll Rand countercurrent flotation separator has been operating as a primary clarifier at a New Hampshire, U.S.A. paper mill (Knapton and Taylor, 1975). The 3.1-m^2, 5.8-m high flotation tank was designed to operate at a hydraulic loading of 8.5 m/h, using 0.75-1.5 mg/g polymer. A float TS of five percent to six percent and effluent SS of 100 mg/L or less was anticipated. Operating performance confirmed these ratings, and a second unit had been ordered at time of writing to be used as a secondary clarifier following extended aeration biological treatment.

In their 1976 article, Chambers and Cottrell give examples of full-scale application of electroflotation and microflotation. Electroflotation has been used in approximately 20 plants in the U.K., treating wastes such as wash liquors from printing units, greasy and fatty wastes from meat processing plants, and effluents from transport trucks. About 19 full-scale microflotation plants are operating in Sweden, and others are under construction in Finland, Norway, the U.K., and Japan. The process has been used on textile effluents, steel mill wastes, and paper mill effluents, among others.

3.6.4 Raw Water and Effluent Polishing. Although considerable pilot plant experience has been obtained in the U.K. on the treatment of raw water by DAF, no reports have been published to date about full-scale installations. The pilot plants used were relatively large (2300 m^3/d; 8.64 m^2) and the fact that their operation has been successful indicates that full-scale operation would also be satisfactory.

Following pilot plant experiments, a full-scale lagoon/DAF system was placed into operation in late 1974 to treat poultry plant wastes (Snider, 1975). Test results indicated performance similar to the pilot plants, but considerably higher hydraulic loading was possible with the full-scale equipment. This was attributed to the greater degree of control possible with full-scale equipment. The economics of the system are presented in brief.

3.7 Comparison Between Sedimentation and Flotation

Probably the most significant general information gained from laboratory and pilot plant work comes from comparisons between sedimentation and flotation for solids separation (Kalinske, 1958; Kalinske and Evans, 1953; Katz, 1964; Vrablik, 1959; Walzer, 1975) and a summary is presented below.

The main advantage of DAF over sedimentation is that a higher rate of dewatering, which occurs with DAF, allows a shorter retention time and, consequently, a smaller unit area. In general, a thicker sludge can be obtained with flotation. This sludge is suitable for aerobic digestion, or for return to the aeration tanks if activated sludge is the secondary treatment process. The process is generally more stable than sedimentation because bulking sludge and others with poor settling characteristics (especially of a transient nature) can be handled without any disruption. Katz (1963), when discussing the operation of DAF, points out that flotation will not remove grit and small, inert, high density particles, an advantage if anaerobic digestion is to succeed flotation. It would also seem apparent, in that case, that flotation could be used for grit removal itself, as part of the application of DAF to the treatment of raw sewage. Provided that a suitable bottom scraper was provided and the pumps could handle the gritty influent, the DAF system could be designed as an integrated primary-solids/grit-removal facility.

The disadvantages of flotation when compared to sedimentation are that the effluent (i.e., subnatant) is poorer, the power and chemical costs are higher, more skilled operation is required, and the mechanical equipment is likely to be less reliable. Kalinske and Evans (1953) state that treatment conditions requiring long contact time, such as the

need for prolonged contact with previously precipitated solids, will not be best served by DAF.

The DAF process could be considered a suitable alternative, or even preferable, to sedimentation, where the quality of the effluent is not critical; where space requirements are limited; where a very thick sludge (say six percent) is required for some subsequent treatment process; and where the suspension to be treated has poor settling characteristics.

3.8 Cost of Flotation

Information on the economics of flotation as an alternative to sedimentation is extremely limited. The earliest report on the air flotation of raw sewage was in 1956 by Thomas H. Hay, the superintendent of the Racine, Wisconsin, primary sewage treatment plant. A "Float-Treat" pilot plant manufactured by the Chain Belt Company was used to compare suspended solids removal by flotation with that in the existing sedimentation tanks. The DAF unit removed 55 to 65 percent of the SS compared to about 50 percent for the settling tanks.

A comparison was made between the cost involved in converting one of the existing sedimentation basins to a flotation unit and the cost of constructing two additional sedimentation tanks. The comparison of capital costs favoured flotation ($50 000 vs. $375 000). Annual operating and maintenance costs for each system were about the same, but only because depreciation costs were included in the annual figures. Obviously, the comparison did not reflect a normal situation, since flotation was given an advantage which would not be typical of most applications.

A study by Mulbarger and Huffman (1970) on mixed liquor solids separation by a full-scale DAF unit was conducted on the 1-mgd (3785-m^3/d) activated sludge plant in Prince William County, Virginia, U.S.A. It compared the cost of flotation clarification with gravity settling plus flotation thickening.

From a cost standpoint, the design criteria selected penalized the DAF process (light loadings) and favoured sedimentation (heavy loadings). The following summary of loadings used by Mulbarger and Huffman reveals this: for flotation, a hydraulic load of 0.25 gpm/ft^2 (0.17 L/m^2•s) and a detention time of 3.4 h was used, while the comparable figures for sedimentation were 0.42 gpm/ft^2 (0.29 L/m^2•s) and 2.3 h, respectively.

Using these criteria, it was estimated that both capital and power costs for DAF were about twice the costs for sedimentation plus flotation thickening of waste

activated sludge. That DAF costs were only double that of sedimentation is probably because the flotation units for this plant in Virginia did not have to be housed in a building as they would in more northerly locations.

In 1974, Mennel reported on a continuous flow bench-scale pilot plant that used lime flocculation of primary effluent, followed by DAF. The primary objective of the study was phosphorus removal. It was estimated that, if carbon adsorption and disinfection were added to the process, a plant cost of \$0.26/1000 gal (\$0.07 per m^3) of wastewater treated in a 10 mgd (38 000 m^3/d) plant would result. Since annual costs in 1974 for a conventional activated sludge plant of this size with phosphorus removal were in the range of \$0.08 to \$0.10/m^3 treated, Mennell's estimate suggests that the proposed physical-chemical system incorporating DAF could be competitive with conventional processes.

Another application involving the economics of flotation separation was described by Snider in 1975. A full-scale 7.5-m diameter DAF unit with full pressurization, used to remove algae from an aerated pond, was loaded for 11 hours per day at about 3 gpm/ft^2 (2 L/m^2•s). Operational costs for alum addition (at 125 mg/L) and for power were calculated as \$0.06/1000 gal (1.6¢/m^3) treated wastewater. Capital costs at \$130 000 suggested that DAF offered a "cost-effective means" for removing algae from wastewater systems. However, the costs presented did not include a building, feed and effluent pumps, or necessary controls. Furthermore, no comparative costs for alternative systems, such as filtration, were offered so the apparent attractiveness of DAF in this study is not adequately substantiated.

An extensive examination of costs for flotation thickening of waste activated sludge at municipal sewage treatment plants was carried out by W.F. McMichael in 1974. Design criteria (with and without flotation aids) and equipment costs were obtained from Komline-Sanderson and Rex-Chainbelt, and installation costs from a general contractor. Graphs are presented for both capital cost and operating and maintenance cost, based on the design capacity of the sewage treatment plant. Plots relating construction costs, man-hour requirements, and material costs to thickener area or to the annual quantity of sludge thickened are also included. The capital costs include necessary buildings and allow 20 percent of construction cost for engineering, legal and administrative charges and 14 percent of construction cost for a proportionate share of the treatment plant yard work. This excellent report contains useful data for assessing the cost of flotation thickening.

The costs of flotation thickening have also been considered by Campbell et al. (1978). The method followed is to use major equipment costs plus mark-up factors (specific to the type of equipment) for installation, insurance, profit, etc. For example, the suggested factor for the capital cost of DAF thickening (excluding buildings) is 2.36 times the FOB cost of the major equipment. Although the factor method for estimating overall costs can serve as a general guide, it is of limited value in detailed cost comparisons where scale-up factors, site conditions and other final local influences may have a bearing.

3.9 Current Research Activity

The activity of some of those involved in DAF research is outlined below to indicate the directions in which DAF research is proceeding.

South African researchers have been pioneers in flotation research for many years. Van Vuuren et al. (1968) and Stander and van Vuuren (1970) are frequently cited for their work in the use of flotation for the tertiary treatment of effluents, and for their general contributions to the theory and practice of flotation. More recently, Bratby and Marais (1975) published a paper regarding basic research into factors affecting flotation performance and the dissolution of air into the recycle liquid. They developed novel methods for saturating the air and measuring the saturation percentage.

Davis (1977) is investigating the use of DAF for the clarification of mixed liquor. Pilot experiments using various sizes of Komline-Sanderson DAF units have been conducted on the mixed liquor from an extended aeration plant with a solids retention time of 25 days. It has been found that the natural bioflocculation of the sludge renders flotation aids unnecessary. Construction of DAF equipment was being planned to serve a 150 000 m^3/d plant that will incorporate biological nitrogen and phosphorus removal.

The Water Research Centre (WRC) at Medmenham, England, is currently investigating the use of DAF for water treatment. Researchers at the centre have developed a versatile batch laboratory flotation unit, as well as a nozzle (patented as the WRC nozzle) to introduce air-laden recycle water to the influent stream. The WRC is at present (1977) coordinating larger-scale flotation studies (2300 m^3/d) with five water authorities to determine the feasibility of using DAF for water treatment on an extensive scale (Hyde, 1977).

The Swiss Federal Institute for Water Resources and Water Pollution Control (Eidgenössische Technische Hochschulen) has been involved in DAF research mainly with respect to bubble generation, bubble size distribution and bubble attachment mechanisms.

Preliminary data on the influence of turbulence on gas precipitation rates and the dosing of gas bubble nuclei to control bubble size indicated some success with regard to low residual turbidities, but the work was discontinued.

E.R. Hayes of Acadia University in Wolfville, Nova Scotia, is examining the flotation process for the removal of colour from paper mill effluents with organic flocculants. No results are yet available.

Most of the manufacturers of DAF equipment conduct their own research programs. Komline-Sanderson, with over 350 DAF units in service, has dominated the municipal field in the flotation thickening of waste activated sludge. Company research efforts have been directed toward optimizing thickener performance and improving the air saturation system. Saturation levels up to 95 percent are claimed for the patented K-S method, i.e., similar to that from "packing" systems. The K-S system is supposedly not susceptible to plugging problems. Efficiency of the air saturator system has also been the principal research activity of Eimco Envirotech.

Imperial Chemical Industries (ICI) promote the microflotation process as developed by Electrolux research in Sweden. Low power requirements and low operating costs are advantages of the units, which utilize an 8-m to 15-m deep shaft through which the liquid passes and low-pressure air is introduced. Hydraulic flow governs normal design (no recirculation) which is intended for solids removal rather than thickening. For use as a sludge thickener, increased aeration would be necessary and recirculation would be added. The 24 plants in operation (1977) attest to the success of the process for water treatment.

Rexnord (and its predecessor Rex-Chainbelt) has, since 1952, concentrated its research activity on thickening rather than separation, because Rexnord felt that the high operating costs could only be justified where oil or grease removal or limited space made flotation separation necessary. However, the treatment of stormwater overflows by flotation has been under investigation for several years and studies on the polishing of algae pond effluent by flotation have just been concluded. Effluent polishing has reportedly been quite successful although no detailed information has been released.

Ingersoll-Rand research has produced a circular, vertical flotation thickener with downward flow countercurrent to the rising bubbles. The unique design, it is claimed, can accept higher hydraulic and solids loading at lower recycle and A/S ratios than conventional DAF. Although the process looks promising, applications to date are limited and none includes clarification of municipal wastes.

Permutit offers the "lamellar" design for flotation in which vertical, longitudinal plates (or lamels) in the horizontal DAF unit maintain laminar flow by decreasing the hydraulic radius. This permits double the hydraulic load of conventional units to be applied. A two-year study on the clarification of mixed liquor indicated that Permutit's Favair II unit cost less initially and required less coagulant than conventional DAF units. Unfortunately, the limited results are insufficient to draw any firm conclusions. Permutit, however, does not recommend flotation clarification for large plants because of the high power requirements for pumping.

3.10 Manufacturers' Literature

Information from correspondence, brochures and other data received from manufacturers cooperating with this study is summarized in Table 1. The expected performances indicated are not guaranteed values but simply the manufacturers' predictions as to how their equipment would perform under the specified conditions using a coagulant. In most cases, an average float concentration of four percent was indicated for both thickening (whether waste activated sludge at 10 000 mg/L or mixed liquor at 4600 mg/L) and clarification (of raw sewage at 200 mg/L or mixed liquor at 2800 mg/L) so float concentration is not shown in the table.

Three manufacturers, Komline-Sanderson, Rexnord and Envirotech, offer comparably designed equipment, typical of the many DAF units now in use. Three other manufacturers Permutit, Ingersoll-Rand and Imperial Chemical offer unique designs which are products of their own research. DAF units are generally available in prefabricated steel tanks up to about 37 m^2 in area with larger sizes available for installation in concrete tanks.

TABLE 1 DAF CRITERIA AND EXPECTED PERFORMANCE USING COAGULANT AIDS

	Design Load					Effluent SS			
	HYD (m/h)	Solid ($kg/m^2 \cdot h$)	Max Recycle Ratio	Max A/S Ratio	Max Pressure (kPa)	Waste Activated Sludge (10 000 mg/L)	Raw Sewage (200 mg/L)	Mixed Liquor (4600 mg/L)	Mixed Liquor (2800 mg/L)
Komline-Sanderson	2.20	9.8	2	.038	480	500	NR	230	140
Rexnord	0.9*	9.8	1	.014	280	1600	90	NR	NR
Envirotech	4.89	9.8	2	.02	520	500	60	250	200
Permutit	12.23	14.6	ANY	NP	480	NP	NP	NP	NP
Ingersoll-Rand	19.56	73.2	1	.02	690	50	NR	NP	NP
Imperial Chemical Industries	7.09	9.8	NIL**	NP	170	NP	NP	NP	NP

* Horizontal velocity in m/min
** Clarification criteria, no coagulant aids
NR Not recommended by manufacturer
NP Not provided by manufacturer

4 EXPERIMENTAL PROGRAM AND APPARATUS

4.1 Three Phases

As noted in Section 2, the feasibility of using DAF to treat wastes from three different sources was investigated. It was logical, therefore, to divide the study into three distinct phases, based on the wastewater sources:

Phase 1 - Extended aeration

Phase 2 - Raw Sewage

Phase 3 - Conventional activated sludge

4.2 Equipment Common to all Phases

4.2.1 Bench-Scale Batch DAF Unit. Instead of the traditional two-cylinder, or "bomb" unit, a three-cylinder batch unit originally developed by Wood and Dick (1973) was used in slightly modified form. This apparatus was successfully used in a previous study by Gehr and Henry (1976).

The three-cylinder batch flotation unit is shown in Figure 1. The essential modification to the Wood and Dick unit was the addition of a dissolved oxygen probe to the pressure cylinder. The probe is described in Appendix B. The dissolved oxygen measurement was used to give a direct indication of the air saturation percentage in the pressurized liquid. Bratby and Marais (1975) demonstrated that the presence of solids in the liquid being pressurized does not affect the amount of air released during flotation. Thus, although air in the recycle liquid (called "recycle" because it is equivalent to pressurized recycle liquid in continuous-flow units) was measured before it was blended with the sludge, it can be assumed that the quantity of air measured will be that actually released, and available for flotation.

Other minor modifications from the Wood and Dick apparatus concerned the valve and piping arrangements and the use of a larger diameter flotation cylinder (140 mm instead of 63 mm) for all experiments.

For the experiments where $FeCl_3$, alum, and lime were used, the chemical was added to the influent (i.e., mixed liquor or raw sewage) prior to flotation. The mixture was stirred rapidly for approximately three minutes, then slowly for 27 minutes, to develop a suitable floc.

4.2.2 Continuous-Flow Pilot DAF Unit. The continuous-flow pilot DAF unit used for all three phases was the Komline-Sanderson SR 15 DAF unit. A schematic of the system, together with ancillary equipment, is shown in Figure 2, and the unit itself in Figure 3.

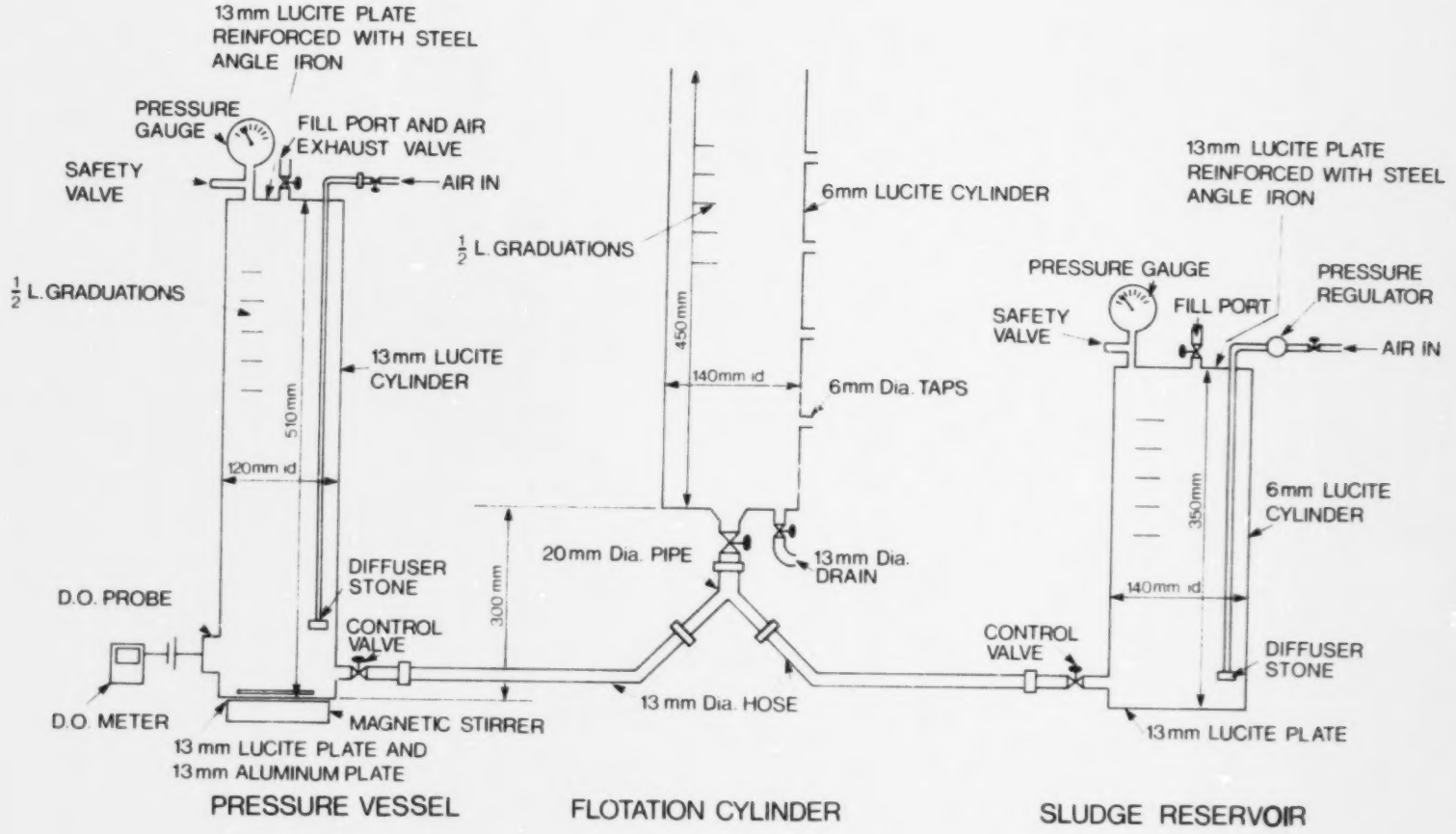

FIGURE 1 BENCH-SCALE BATCH DAF UNIT

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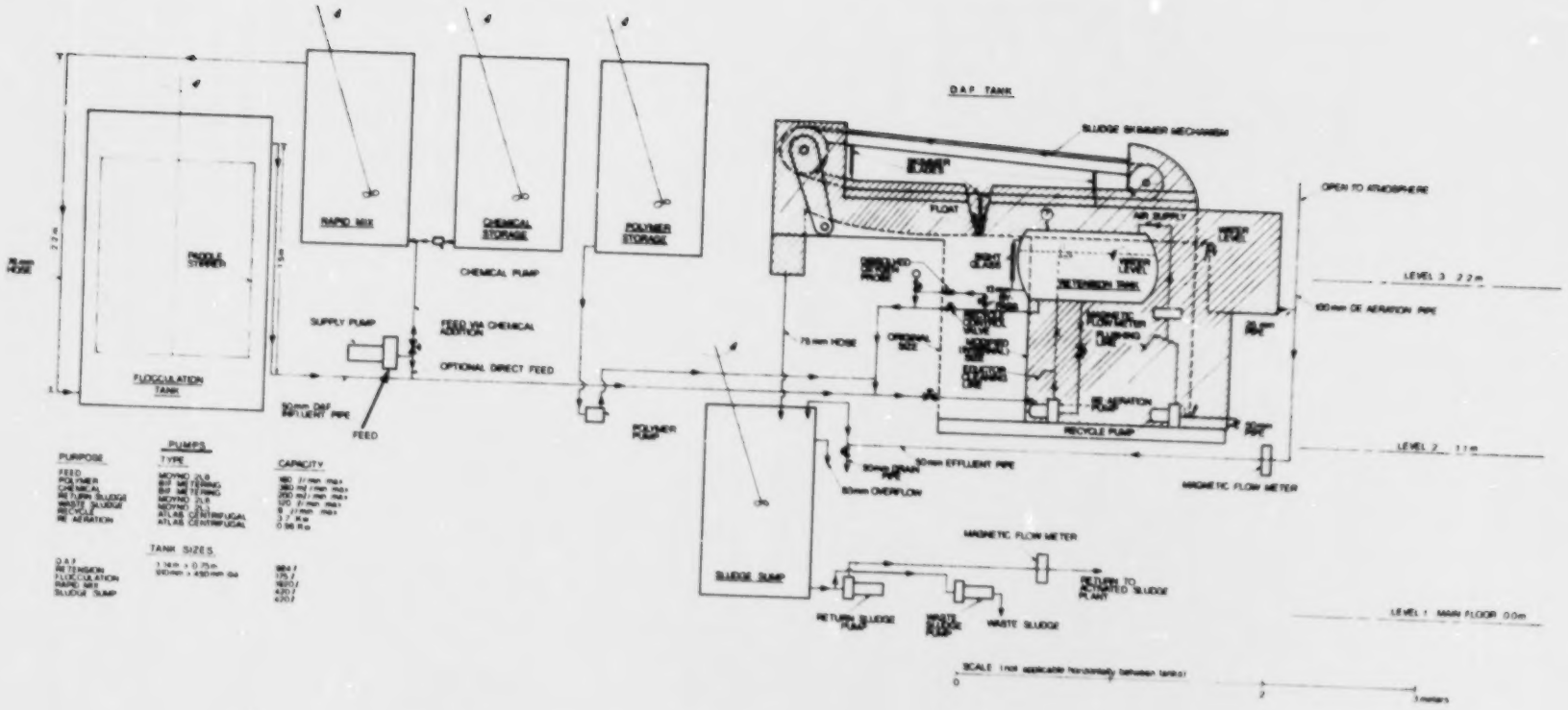

FIGURE 2 DAF PILOT PLANT FLOW DIAGRAM

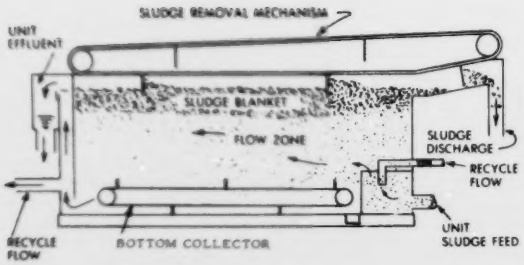

FIGURE 3 INTERNAL FLOW DIAGRAM.
KOMLINE-SANDERSON
SR 15 DAF UNIT

The flotation tank, originally of 1.39 m^2 nominal area, was reduced to 0.836 m^2 nominal area to allow greater flexibility of hydraulic loading when using the existing limited facilities for the supply of raw sewage and activated sludge mixed liquor. The actual dimensions were 1.14 m by 0.75 m by 1.15 m deep, to give an area of 0.856 m^2 and a capacity of 0.984 m^3. The scraping mechanism to remove floated sludge was a continuous-chain with three scraper blades; speed was fixed at 1.8 m/min, and control was by automatic timer. The recirculation and re-aeration pumps were driven by 3.7 kW and 0.56 kW motors, respectively. The pressure tank had a capacity of 160 L, and the operating pressure varied between 330 kPa and 400 kPa. Compressed air at about 550 kPa was injected into the recycle feed to the tank, and the water level in the pressure tank was controlled automatically. Air was mixed with the liquid at the elevated pressure by means of the recirculation pump, which forced the liquid through an eductor inside the tank and created a saturation of approximately 60 percent by venturi action. The recycle flow, measured by a magnetic flow meter, was controlled by a diaphragm valve at the outlet of the pressure tank. The dissolved oxygen in the air-charged liquid was measured by a dissolved oxygen probe attached to a by-pass line over the recycle control valve.

The flotation system was operated on a 24-hour basis, with two complete sets of samples being taken per normal working day. Continuous runs for up to 2 1/2 weeks were achieved.

4.2.3 Ancillary Equipment. Polymer was mixed to a concentration of 0.1 percent (1 g/L) and was fed directly into the recycle liquid just prior to mixing with the DAF influent. A BIF metering pump with a maximum capacity of 390 mL/min was used, and the flow could be measured at any time by means of a graduated column.

Although it is common practice in sewage treatment to add chemicals for phosphorus removal to the aeration tank, in this study both phosphorus removal itself, and the effects which the chemical would have on flotation performance, were studied. Hence, the chemical was added to a rapid mix and flocculating tank combination, preceding the DAF unit. This same system could then be used for the raw sewage section of the study, where an aeration tank would obviously not be available for mixing. The rapid mix tank had a capacity of 0.42 m^3, and the flocculating tank, which included a slow paddle stirrer, had a capacity of 1.92 m^3. Ferric chloride was chosen on the basis of jar and batch flotation tests for phosphorus removal in the pilot plant, and for convenience it will often be referred to simply as "chemical". The number of bound water molecules was determined to be six. The ferric chloride was stored as a solution, and fed to the rapid mix tank by a BIF metering pump of maximum capacity 200 mL/min.

Dissolved oxygen was measured by means of a Beckman Model 7002 dissolved oxygen monitor. The probe was inserted into a flow-through chamber that acted as a by-pass to the recycle control valve. In this way, pressure on the probe membrane was created by the head difference across the control valve, and did not exceed 138 kPa. The measurement procedures used are detailed in Appendix A.

Influent, effluent, recycle, and return sludge flows were measured by magnetic flow meters.

4.2.4 Dye Studies. Dye studies were conducted on the DAF pilot plant prior to modification (i.e., at 1.39 m^2 surface area) and on the unit as used for the study (i.e., at 0.86 m^2 surface area). Rhodamine WT fluorescent dye in a fresh water feed was used. Impulse doses of the dye were fed into the unit, and the effluent monitored using a flourometer and chart recorder.

Since tracer studies had previously been conducted on the DAF pilot plant (Huether, 1974), the purpose of these tests was only to compare characteristics of the larger and smaller tanks. The earlier studies had shown that flow through the larger tank was close to ideal mixed flow; that for adequate mixing action the recycle should be equal to or greater than the influent flow; and that the maximum total hydraulic loading should not exceed 227 L/min. The results of the dye studies are given in the Appendix C. The

conclusion drawn was that the new inlet arrangement would reduce or eliminate short circuiting, and that the smaller tank should otherwise have similar hydraulic characteristics to the large one, i.e., that it could be considered as completely mixed, and suitable for flotation operation.

It should be noted that these dye tests do not account for flow patterns set up by rising sludge flocs. The purpose was to determine whether there was any likelihood of short-circuiting, and floc carry-over with the effluent (subnatant). The tests showed that this condition would be unlikely; the effect of the flow lines set up by the rising flocs would in fact tend to reduce the chances of carry-over.

4.2.5 Jar Tests. One aim of the flotation study was to assess the impact of phosphorus removal chemicals on flotation performance. The actual effectiveness of a particular chemical for phosphorus removal was not a major concern, but it was felt that simple tests should be done to select that chemical most likely to be used for phosphorus removal. The most convenient test for determining this was the jar test. It should be pointed out, however, that the optimum chemical for removing phosphorus under settling conditions, as illustrated by the jar tests, may not be the best for phosphorus removal when DAF is applied. A comprehensive study would be needed to evaluate the interrelationship between the efficiency of phosphorus removal and the impact that the particular chemical had on flotation. This interrelationship was summarily studied using the batch flotation unit.

The jar test apparatus consisted of the standard Phipps and Bird six-place stirrer and light table. One-litre capacity square jars 90 mm x 90 mm were used. A stirrer speed of 100 rpm for three minutes was followed by stirring at 30 rpm for 27 minutes, and quiescent settling for 30 minutes. Total and dissolved phosphorus measurements of the original liquid and supernatant were taken. The final choice of chemical, subject to ratification by the batch DAF tests, was based on cost, frequency of use in treatment plants in Ontario, and ease of handling. Results for all the phases are presented in Appendix D, and will also be referred to briefly where applicable under each phase.

4.3 Phase 1 (Extended Aeration)

4.3.1 Equipment Specific to This Phase. Mixed liquor was supplied from an extended aeration pilot plant (Figure 4) with a retention time of 24 hours at the operating flow of 91 L/min. The F/M ratio was approximately 0.03/day. Aeration by submerged diffusers

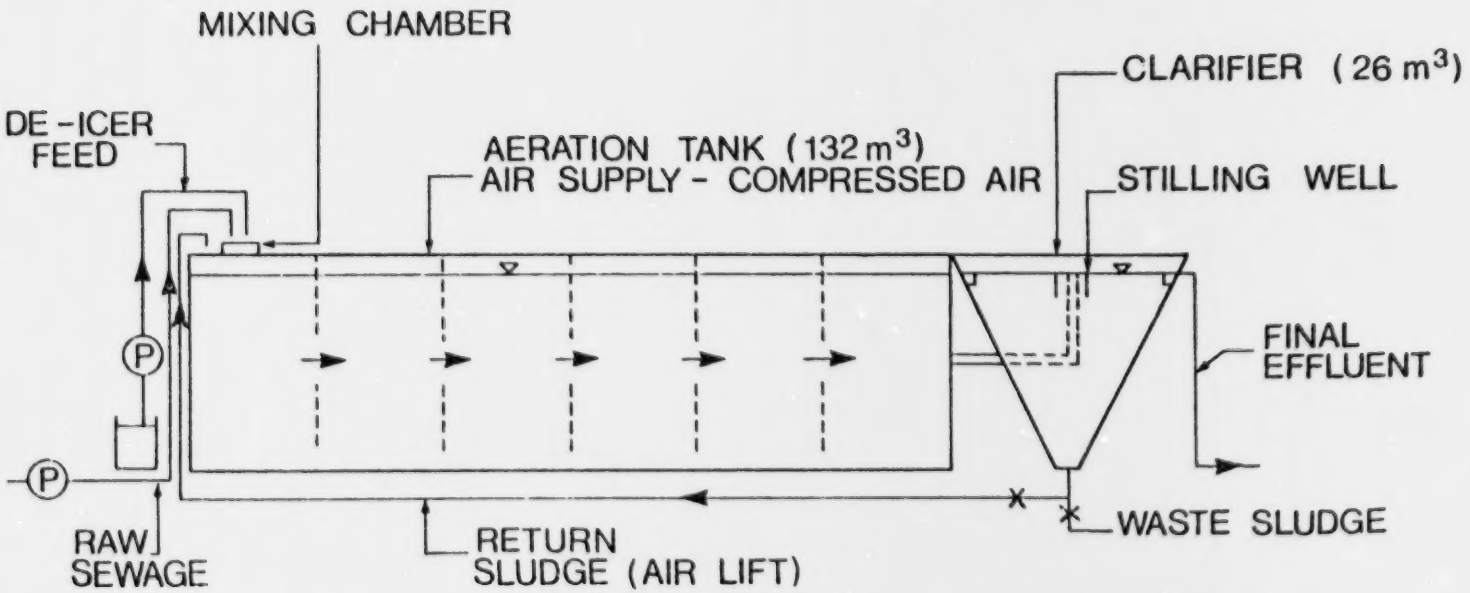

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FIGURE 4 EXTENDED AERATION PILOT PLANT (Jank, et al., 1974)

maintained a DO above 2 mg/L, and since the reactor was divided into compartments, a tendency towards plug flow rather than complete mixing was expected.

The aeration tank effluent was pumped directly from the outlet end of the aeration basin to the DAF unit. After the flotation process, the two separated streams (float and subnatant) were combined in a sump and pumped back to the aeration basin inlet. In this way, the flow to the flotation system could be varied while operation of the extended aeration plant was maintained at constant loading.

4.3.2 Constraints. Initial operating problems and modifications to the DAF pilot plant caused serious delays in this phase of the study (see Section 5.3). When steady operation was achieved, two weeks were available for experimentation before cold weather conditions forced termination of the operation of the extended aeration pilot plant.

4.3.3 Jar Tests. Using the apparatus as described in section 4.2.5, the following phosphorus removal chemicals and dosages were tested:

Alum: 60, 120, 150, 180, 240 mg/L
Ferric chloride: 5, 10, 15, 20, 40, 60, 120, 150, 180, 240 mg/L
Lime: 60, 120, 150, 180, 240 mg/L

One control (no chemical addition) was used for each set of five jar tests, i.e., one for alum and lime, and two for ferric chloride. The supernatant was tested for total and soluble phosphorus.

4.3.4 Batch Flotation Tests. Batch flotation tests on the mixed liquor were performed in order to obtain approximate operating values for the pilot plant. Factors of concern were the air to solids ratio (A/S), polymer type and dosage, and the effect of the three phosphorus removal chemicals on flotation behaviour. Parameters used to characterize flotation performance were float and effluent solids concentrations, thickening parameter (defined in Appendix A) and soluble phosphorus reduction.

The following experimental program was followed:

1) Determination of optimum A/S; 11 tests.
   Pressures: 207, 276, 310, and 345 kPa
   A/S ratio: 0.00618 to 0.0261.
2) Choice of polymer; 31 tests, 10 polymers:

   Percol: 728, 744, 751, 757

Calgon: WT 2870, E 270L, Catfloc A

Hercofloc: 834, 849, 855

3) Determination of optimum polymer dose; 12 tests.

4) Effect of chemical addition (for P removal) in conjunction with the selected polymer (Percol 757). Twelve tests were carried out using alum, ferric chloride, and lime at high and low doses in conjunction with varying polymer concentrations. The concentrations used are discussed in Section 5.2.4 and shown in Table 12.

5) Three tests to demonstrate the effect of chemical addition (optimum chemical, i.e., ferric chloride) on flotation without polymer addition.

4.3.5 Pilot Tests. The plant was started on five occasions, each of which in turn resulted in failure and plant modifications. The modifications included:

a) replacing the 37-mm diaphragm valve used to control the recycle flow with a 19-mm diaphragm valve;

b) lowering the flotation tank liquid level by removing weir plate;

c) reducing paddle stirrer speed to ensure continuous operation (at the original speed, the stirrer motor would strip periodically, causing anaerobiosis in the flocculating tank, and solids slugs to enter the flotation tank);

d) installing the appropriate valves to allow the eductor to be cleaned while the plant was running (see Figure 8);

e) installing a solids and hair collection chamber ahead of the pressure tank to minimize line plugging.

The following experimental program was then followed:

1) A/S variation

Range of A/S: 0.0102 to 0.0381

Range of recycle ratio: 0.86 to 4.17

Number of tests conducted: 11

Operating conditions are shown in Table 2.

2) Effects of chemical addition:

Chemical added: $FeCl_3 \cdot 6H_2O$

Range of doses: 15 - 60 mg/L

Operating conditions: see Table 3.

3) Effects of stressing the DAF unit with high loads, and low polymer dose and A/S ratio.

Test details are shown in Table 4.

TABLE 2 OPERATING CONDITIONS TO STUDY THE EFFECTS OF A/S VARIATION. DAF PILOT PLANT PHASE 1

	Polymer Dose (mg/g)	Pressure (kPa)	Inf. SS (mg/L)	Inf. Flow (L/min)	Hydr Load (m/h)	Solids Load ($kg/m^2 \cdot h$)
Mean	0.92	380	4500	32	2.27	10.0
σ	0.076	14	183	-	-	0.45

TABLE 3 OPERATING CONDITIONS TO STUDY THE EFFECTS OF CHEMICAL ADDITION. DAF PILOT PLANT PHASE 1

	Polymer Dose (mg/g)	Pressure (kPa)	Inf. SS (mg/L)	Inf. Flow (L/min)	Hydr Load (m/h)	Solids Load ($kg/m^2 \cdot h$)	A/S
Mean	0.86	386	4750	32	2.27	10.8	0.030
σ	0.03	-	145	-	-	0.34	0.005

TABLE 4 OPERATING CONDITIONS TO STUDY THE EFFECTS OF STRESSING THE DAF SYSTEM. DAF PILOT PLANT PHASE 1

Test Description	Polymer Dose (mg/g)	Pressure (kPa)	Inf. SS (mg/L)	Infl. Flow (L/min)	Hydr. Load (m/h)	Solids Load ($kg/m^2 \cdot h$)	A/S Ratio	Chemical Dose (mg/L)
Low polymer and Low A/S	0.42	407	4500	32	2.27	10.3	0.0194	60
Low polymer and A/S; high hydraulic and solids loads	0.53	379	5570	55	3.91	21.8	0.0120	60

4.4 Phase 2 (Raw Sewage)

4.4.1 Equipment Specific to this Phase. Screened raw sewage was supplied from the Burlington Skyway Sewage Treatment Plant. This plant treats predominantly domestic sewage from a population of 75 000.

4.4.2 Constraints. The quality of the raw sewage, in terms of SS and COD was so variable (SS, 60 - 500 mg/L; COD, 130 - 750 mg/L) that it was impossible to separate the effects of the controlled variables, such as A/S, from this influent variation.

Flow rate to the pilot plant was controlled and held constant over any chosen period. The effect of diurnal flow variations on flotation was not studied.

4.4.3 Jar Tests. Using the standard apparatus as described in Section 4.2.5, the following phosphorus removal chemicals and dosages were tested:

alum: 60, 120, 150, 180, 240 mg/L
ferric chloride: 15, 25, 35, 45, 65 mg/L
lime: 60, 120, 150, 180, 240 mg/L

A control jar (no chemical addition) was used for each of the three sets of tests. The supernatant was tested for total and soluble phosphorus.

4.4.4 Batch Flotation Tests. Batch tests were done to obtain operating values for the pilot plant, and the same variables as in phase 1 were considered.

The following experimental program was followed:

1) Determination of optimum A/S; seven tests.
   Pressure: constant at 276 kPa
   A/S: 0.0875 to 0.683
2) Choice of polymer; 52 tests, 17 polymers.
   Percol: 720, 725, 726, 730, 757, 763
   Calgon: E207L, M540, M600, WT2690, WT2870, WT3000
   Hercofloc: 812, 815, 818, 831, 855
3) Determination of optimum polymer dose; 13 test results extracted from (2) above.
4) Comparison of recycle liquids - water or DAF pilot plant effluent; four tests using each liquid, i.e., eight tests.
5) Ferric chloride addition vs. alum addition (no polymer); eight tests.
   $FeCl_3$ dose: 10, 25, 25, 40 mg/L
   Alum dose: 40, 50, 100, 160 mg/L

6) Tests with ferric chloride alone, and comparison with no chemical addition. $FeCl_3$ dose: 0, 15, 30 mg/L

7) $FeCl_3$/Percol 757 interaction; four tests. See Table 5.

TABLE 5 CHEMICAL AND POLYMER DOSES TO STUDY THE INTERACTION EFFECTS. DAF BATCH UNIT PHASE 2

Test No.	$FeCl_3$ dose (mg/L)	Percol 757 dose (mg/L)
1	25	0.59
2	25	1.57
3	25	1.76
4	25	2.20

4.4.5 Pilot Tests. Because of the wide variation of influent solids concentration, values quoted below for the experimental program are on a volumetric rather than mass basis, i.e., mg/L instead of mg/g for polymer dosage, and recycle ratio instead of A/S.

The following experimental program was followed based on four distinct sets of chemical and/or polymer addition:

1) No additions (Table 6)
2) Polymer (Percol 757) addition (Table 7)
3) Ferric chloride addition (Table 8)
4) Polymer plus ferric chloride addition (Table 9)

TABLE 6 OPERATING CONDITIONS. NO ADDITIONS DAF PILOT PLANT PHASE 2

Inflow (L/min)	Recycle Ratio	Polymer (mg/L)	$FeCl_3$ (mg/L)	Number of Tests
45	1.6	-	-	4
91	0.65-1.25	-	-	14
109	0.25-0.66	-	-	4

TABLE 7 OPERATING CONDITIONS TO STUDY THE EFFECTS OF POLYMER ADDITION. DAF PILOT PLANT PHASE 2

Inflow (L/min)	Recycle Ratio		Polymer (mg/L)	$FeCl_3$ (mg/L)	Number of Tests
109	0.56		0.22	-	2
91	mean	1.13	0.22	-	5
91	σ	0.18	0.44	-	8
91			0.55	-	3
91			0.66	-	3
91	0.8		0.88	-	3

TABLE 8 OPERATING CONDITIONS TO STUDY THE EFFECT OF CHEMICAL ADDITION. DAF PILOT PLANT PHASE 2

Inflow (L/min)	Recycle Ratio	Polymer (mg/L)	$FeCl_3$ (mg/L)	Number of Tests
45	1.6	-	24	3
91	0.7	-	25	3
91	0.7	-	42	4
91	0.8	-	51	2
136	0.7	-	20	3
136	0.7	-	25	1

TABLE 9 OPERATING CONDITIONS TO STUDY THE EFFECTS OF BOTH POLYMER AND CHEMICAL ADDITION. DAF PILOT PLANT PHASE 2

Inflow (L/min)	Recycle Ratio	Polymer (mg/L)	$FeCl_3$ (mg/L)	Number of Tests
91	0.8	0.88	51	3
109	0.66	0.18	27	2
109	0.66	0.37	27	2
136	0.8	0.88	50	3

4.5 Phase 3 (Conventional Activated Sludge)

4.5.1 Equipment Specific to This Phase. Mixed liquor at a solids concentration of about 3000 mg/L was supplied from a pilot-plant aeration tank with retention time of four hours at the operating flow of 91 L/min. The F/M ratio was approximately 0.35. The reactor approximated completely stirred conditions because only one compartment was used.

Aeration, DO levels, and pumping arrangements to and from the DAF unit were the same as for phase 1.

4.5.2 Jar Tests. Using the standard apparatus as described in Section 4.2.5, the following phosphorus removal chemicals and dosages were tested:

alum: 60, 120, 150, 180, 240 mg/L
ferric chloride: 10, 25, 40, 50, 60 mg/L

A control (no chemical addition) was used for each of the two sets of tests. The supernatant was tested for total and soluble phosphorus.

4.5.3 Batch Flotation Tests (see Appendix G). Batch flotation tests to obtain operating values for the pilot DAF unit were conducted as in phases 1 and 2, except that the various polymers used during the initial selection procedure were dosed on an equal cost basis to reduce the number of tests. This method was found to be more convenient than the one previously used, which was based on equal dosages.

The following experimental program was followed:

1) Determination of optimum A/S; six tests.
   A/S: 0.0127 to 0.0589
2) Selection of polymer; 12 tests, 12 polymers.
   Percol: 720, 722, 728, 757, 763, 776
   Calgon: WT2690, WT3000
   Hercofloc: 812, 815, 849, 855
3) Comparison of the best two polymers, i.e., Percol 728 and Hercofloc 849; six tests. For tests conducted under 2) and 3), polymer choice was made on the basis of float effluent solids concentration.
4) Determination of optimum dosage for the polymer selected, i.e., Percol 728; six tests.

Dose range: 0 - 1.7 mg/g.

5) Effect of $FeCl_3$ addition on flotation performance, and assessment of $FeCl_3$/polymer interaction. See Table 10 for conditions used in the six tests. Performance was assessed on the basis of float and effluent solids concentration.

TABLE 10 CHEMICAL AND POLYMER DOSES TO STUDY THE INTERACTION EFFECTS. DAF BATCH UNIT PHASE 3

Test	Polymer dose (mg/g)	$FeCl_3$ dose (mg/L)
1	0	0
2	0	25
3	1.9	25
4	1.9	15
5	1.7	35
6	1.7	45

4.5.4 Pilot Tests. Since it was expected that mixed liquor solids concentration could be consistently maintained at 3000 mg/L, and that the other dependent variables could be controlled within a narrow range, a 2^{4-1} fractional factorial design program with at least three replicates formed the basis of the experimental work in this section (Davies, 1956). The independent variables were chosen on the basis of the batch tests and are shown in Table 11. Also described in Table 11 are additional tests conducted to study specific conditions.

TABLE 11 FRACTIONAL FACTORIAL DESIGN PROGRAM. DAF PILOT PLANT PHASE 3

Treatment No.	Replicates	A/S	Polymer (mg/g)	Influent (L/min)	$FeCl_3$ (mg/L)
1	4	0.028	0.88	45	25
2	4	0.028	0.88	68	0
3	3	0.028	1.39	45	0
4	3	0.028	1.39	68	25
5	4	0.041	0.88	45	0
6	3	0.041	0.88	68	25
7	4	0.041	1.39	45	25
8	4	0.041	1.39	68	0
Additional ("Extreme") Tests					
9	3	0.029	0.80	45	0
10	3	0.041	1.36	45	0
11	3	0.026	1.40	68	0
Low polymer dose					
12	1	0.032	0.43	45	0
13	1	0.027	0.48	68	0
14	1	0.044	0.67	68	0
15	2	0.030	0.44	45	25
High influent flow					
16	3	0.020	0.91	91	0

5 EXPERIMENTAL RESULTS AND DISCUSSION - PHASE 1 (EXTENDED AERATION)

5.1 Jar Tests

For the chemicals tested, the minimum doses required to give an effluent containing less than 0.5 mg/L soluble phosphorus with total phosphorus content less than or equal to 1.0 mg/L were:

Chemical	Dose (mg/L)	Soluble P (mg/L)	Total P (mg/L)
Alum	150	0.0	0.1
$FeCl_3$	60	0.1	0.2
Lime	120	0.3	1.0

These tests showed clearly that ferric chloride would require the lowest dosage. On a unit cost basis ferric chloride is also the cheapest. (See Appendix D.)

Other considerations involved in the choice of chemical were physical characteristics and acceptability in Ontario. Lime, for example, is unpopular because it is troublesome to handle in its dry or slurry forms, and produces a heavy floc that could be difficult to float. Ferric chloride is the most popular chemical in Ontario for phosphorus removal.

Based on the above considerations, it was concluded that ferric chloride would be the most suitable chemical for phosphorus removal, and that this chemical should be used to study the impact of phosphorus removal chemicals on DAF performance.

5.2 Batch Flotation Tests

5.2.1 Determination of Optimum A/S. Mixed liquor from the extended aeration plant was used as feed sludge, and effluent from the same plant as "recycle" in 11 batch flotation tests conducted to determine the optimum A/S ratio. The results are shown in Figures 5 and 6.

a) No distinct trend appeared for effluent solids vs. A/S (Figure 5a).

b) Float solids vs. A/S (Figure 5b , the traditional graph for flotation evaluation) does give fair linear correlation (0.73). The gentle slope indicates that A/S variation had a relatively small effect on float solids. A better plot (linear correlation 0.96) is

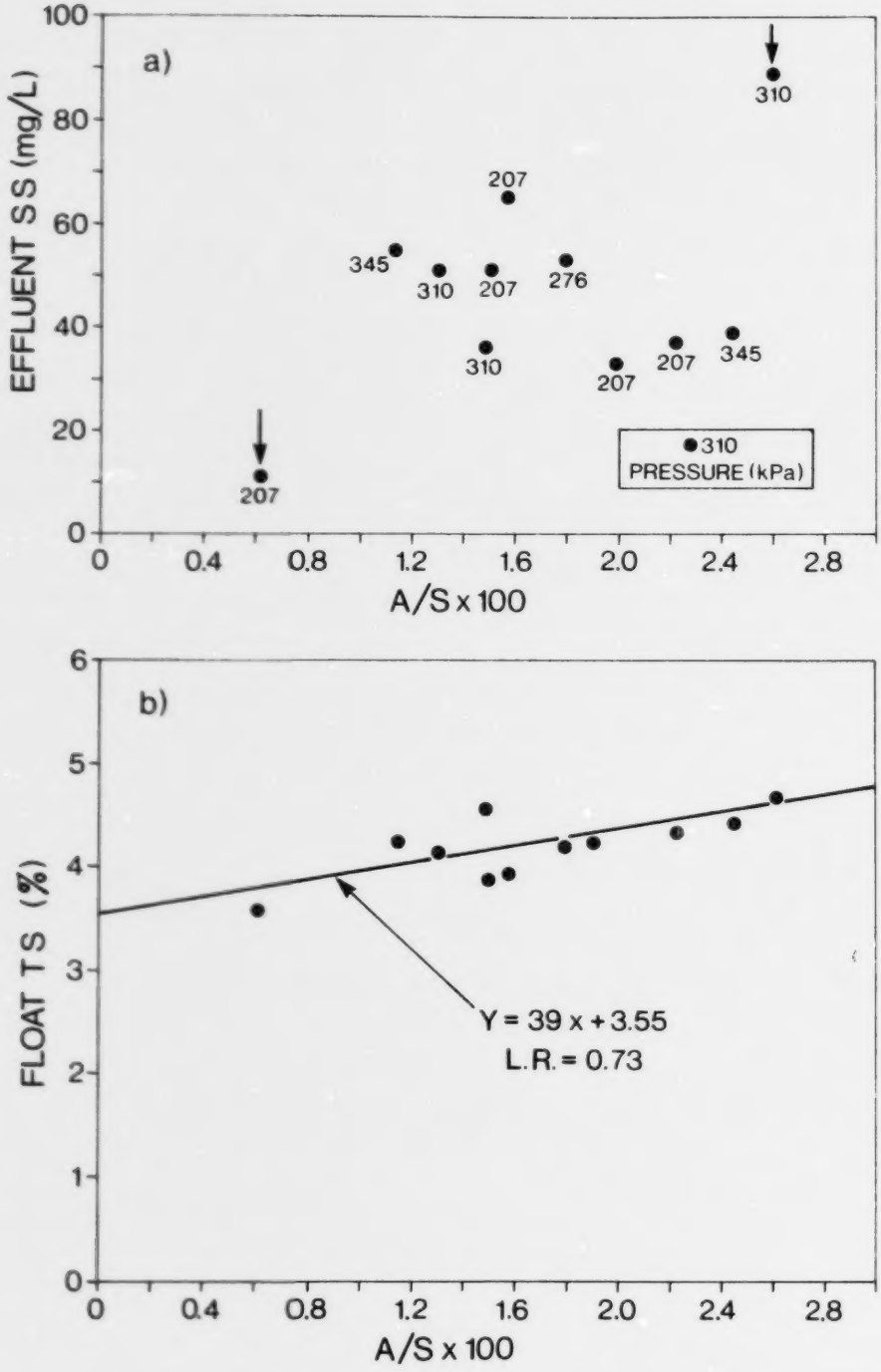

FIGURE 5 FLOAT AND EFFLUENT SOLIDS vs. A/S, NO POLYMER. DAF BATCH FLOTATION UNIT PHASE 1

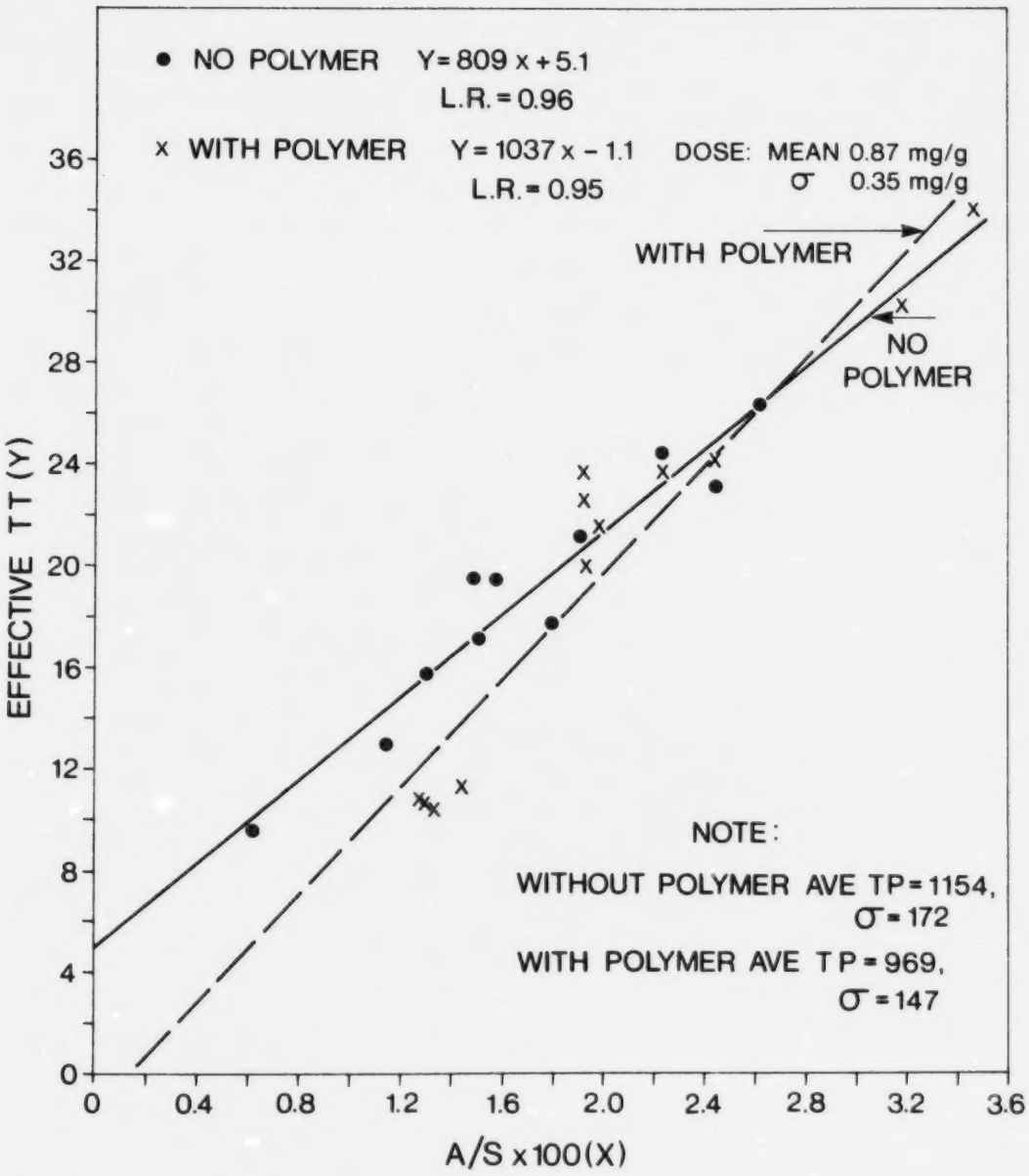

FIGURE 6 EFFECTIVE TIMES THICKENING vs. A/S DAF BATCH FLOTATION UNIT. PHASE 1

obtained for effective times thickening (Eff. TT) vs. A/S, where Eff. TT is the ratio of the float to effective influent solids concentrations (Figure 6). The slope of this graph (809) would be equivalent to the thickening parameter (TP), where TP = Eff. TT ÷ A/S (Gehr and Henry, 1976) if the line passed through the origin. However, it can be shown statistically that this equality does not hold at the 95 percent confidence level. For this case of flotation thickening, therefore, performance would be inadequately characterized by the thickening parameter (in fact, its value ranges between 943 and 1552 with a mean of 1154). The most useful way to characterize performance would be by means of a graph of effective times thickening vs. A/S, or a thickening equation. The application of the thickening parameter and thickening equation is described in detail in Appendix E.

c) Pressure variation had no consistent effect on float or effluent solids concentration.

d) The batch flotation tests gave no clear indication of the optimum A/S but, at a value of around 0.02, both float and effluent solids were close to their highest and lowest values, respectively. This value was chosen for subsequent batch tests.

5.2.2 Choice of Polymer. The ideal program of tests for the choice of polymer would be a series of tests at different doses of each polymer, followed by a cost analysis based on the optimum dose in each series. Time limitations inevitably precluded such a scheme, and Percol 757 was finally chosen in this study because it:

a) produced the thickest float;

b) gave effluent solids as low as with any other polymer; and

c) was available in micro-bead form, allowing for easy mixing into solution.

Percol 757, a high organic polymer, did not have the lowest unit price of those tested (Percol 728, used for phase 3, had the lowest price) but the advantage of its high performance was thought to outweigh the cost. It should be stressed that Percol 757 is not being recommended for general flotation thickening; it was found to be efficient under the experimental conditions used.

5.2.3 Optimum Polymer Dose. No clear trend emerged from the 12 tests carried out. This may be accounted for by the inability to maintain a constant A/S, which could have affected float concentration. The addition of polymer caused a general decrease in effluent solids concentration (down from an average of 47 mg/L to 14 mg/L), but actual variation with polymer dosage could not be correlated. In this instance, such low levels of

solids concentration could not be measured accurately enough. Figure 7 indicates that the addition of 0.7 - 0.9 mg/g polymer gave the best effluent, and this range was chosen for the pilot tests.

Although it appears from Figure 7b that no benefit in terms of float concentration would be obtained by polymer addition (this agrees with previous results obtained by Gehr and Henry (1978)), the nature of the process has changed. This is shown in Figure 6 by the slope of the effective times thickening vs. A/S line. The TP slope (1037) and TP (969) can be regarded as being equal at the five percent level of significance, in contrast with the result for the comparison of these values when polymer was not used. These results can be interpreted to indicate that performance is more stable when a polymer is used, and can be more clearly characterized by theoretical parameters, in this case, the thickening parameter.

5.2.4 Effects of Phosphorus Removal Chemicals (in conjunction with the selected Polymer) on Batch Flotation Tests. The results of these tests, all conducted at 276 kPa and with extended aeration effluent as recycle, are shown in Table 12.

One anomaly immediately apparent is that lime addition appears to cause a release of soluble phosphorus. Clearly this effect would make lime unsuitable for use in conjunction with flotation if it were true. No explanation was found for this peculiar result, and the effect was not studied further because lime was rejected for other reasons. The following conclusions may be drawn from Table 12:

a) The high influent solids concentration of the first three tests did not affect the results, probably because the A/S and polymer dose on a mass basis was kept consistent with the other sets of tests.

b) The effluent in the case of lime addition was substantially worse than that for the other two chemicals.

c) Phosphorus removal chemicals had no obvious effect on float solids concentration (Figure 7b).

d) The higher chemical dosage has neither a positive nor a negative effect on effluent solids concentration, but as expected, a higher chemical dose leads to a greater percentage of soluble phosphorus reduction, except for the single (maverick) exception of test 7.

On the basis of these tests, alum and $FeCl_3$ are approximately equally efficient in terms of phosphorus removal, but overall flotation performance is better when $FeCl_3$ is used.

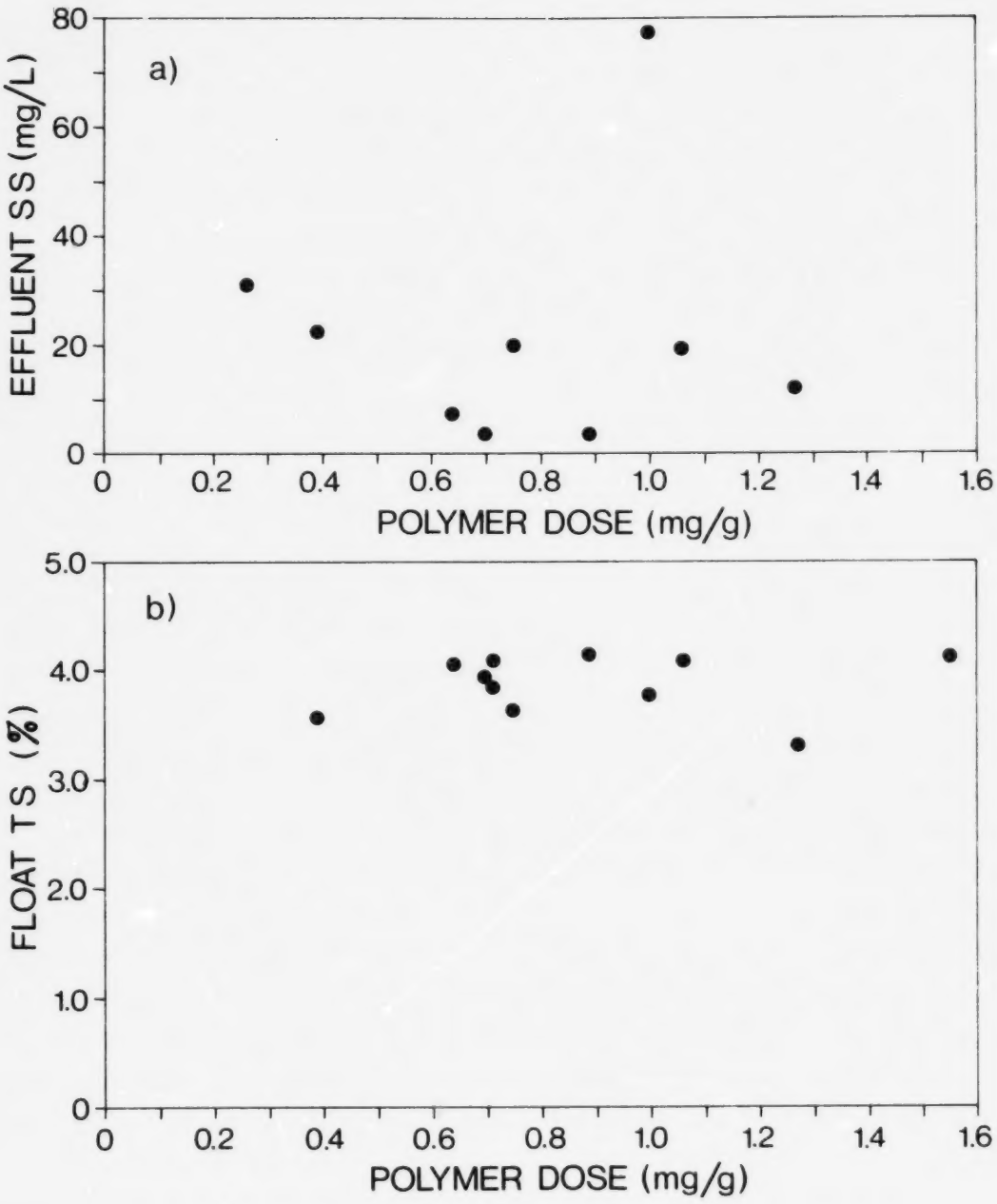

FIGURE 7 EFFECT OF POLYMER ADDITION ON FLOAT AND EFFLUENT SOLIDS. DAF BATCH FLOTATION UNIT PHASE I

TABLE 12 EFFECTS OF CHEMICAL ADDITION ON FLOTATION WITH POLYMER. DAF BATCH FLOTATION UNIT PHASE 1

Test	Chemical	Dose (mg/L)	Polymer Dose (mg/g)	A/S x 100	Influent SS (mg/L)	Effluent SS (mg/L)	Float TS (%)	Soluble P reduction mass basis (%)
1	Alum	150	0.98	1.32	6471	24	3.74	63
2	$FeCl_3$	60	0.98	1.41	6471	34	3.52	65
3	Lime	120	0.78	1.26	6471	49	3.44	-87
4	Alum	150	0.83	1.95	4008	42	3.89	49
5	$FeCl_3$	60	0.83	2.01	4008	27	3.53	58
6	Lime	120	0.83	2.10	4008	97	3.92	-48
7	Alum	75	1.25	1.55	4404	20	3.82	65
8	$FeCl_3$	30	1.25	1.49	4404	23	3.80	53
9	Lime	60	1.25	1.54	4404	109	3.93	-13
10	Alum	75	0.71	1.58	4693	32	3.71	33
11	$FeCl_3$	30	0.71	1.31	4693	27	4.01	7.5
12	Lime	60	0.71	1.38	4693	49	4.13	-11

Phosphorus removal itself is similar for alum and $FeCl_3$ when a dose ratio of 2.5:1 is used. This confirms the jar test results (Section 5.1).

5.2.5 Effect of $FeCl_3$ on Batch Flotation, Without Polymer. Ferric chloride had no significant effect on float solids concentration, but the effluent solids concentration did increase marginally (33%) as $FeCl_3$ dose increased. However, this increase is small compared with the $FeCl_3$ range of doses, i.e., 300 percent. When compared with the effluent quality from the previous three sets of tests, it is noted that the effluent from this set, which used FeCL3 without polymer, had a similar solids concentration to the effluent from set 5.2.1, i.e., no addition at all (see Figure 5). Thus, $FeCl_3$ addition did not improve effluent quality either, although this improvement might have been expected from experience with gravity clarification in the water treatment field (see Table 13).

Unfortunately, measurements of influent solids phosphorus were improperly done, and the phosphorus reduction results were inconclusive.

TABLE 13 EFFECT OF $FeCl_3$ ON FLOTATION WITHOUT POLYMER. DAF BATCH FLOTATION UNIT PHASE 1

Test	Chemical Dose (mg/L)	A/S x 100	Influent SS (mg/L)	Effluent SS (mg/L)	Float TS (%)	Sol. P Reduction mass basis (%)
1	15	1.96	4032	40	4.06	Inconclusive
2	30	1.86	4032	45	4.26	Inconclusive
3	60	2.02	4032	53	4.19	Inconclusive

It was concluded from batch tests that $FeCl_3$ was the most suitable phosphorus removal chemical for use with flotation. At a reasonable dose (< 60 mg/L) $FeCl_3$ should not affect flotation performance.

5.3 Pilot Plant Operation

As might be expected most of the operating problems with the DAF system were encountered in phase 1. The equipment had not been used continuously before. The problems detailed below should be typical of a full-scale DAF unit, and the solutions applied would also be applicable to larger units operating in the field.

The major operating problem with the DAF unit was the air dissolution system. Between the outlet of the flotation tank and the point where recycle liquid, charged with air, enters the tank again, three trouble-spots were identified: the level control system in the pressure tank; the eductor and re-aeration system; and the recycle control valve.

It was anticipated that one of the causes of trouble in such an air dissolution system would be hair and lint in the influent, and that straining could be employed to remove these offenders. However, a strainer was found impractical in the recycle line; when the strainer was used ahead of the pressure tank, it clogged very rapidly when the recycle liquid quality deteriorated, even momentarily. The strainer chamber was retained, however, and it did remove some of the solids. A permanent solution to this problem in the field would be some form of preliminary screening or settling.

Other operating problems encountered during this phase involved the polymer addition system, dissolved oxygen measurements, skimmer operation, and sludge accumulations on various parts of the flotation tank and associated mechanical equipment.

5.3.1 Level Control System. The Komline-Sanderson air dissolution system relies on a fixed water level being maintained in the pressure tank. This level is monitored in a

sight glass, both visually and by a flexible small-bore tube with one end at the desired level and the other connected remotely to a liquid sensor. When the water level submerges the tube end, the liquid travels to the sensor, which in turn triggers a solenoid valve that forces additional air, at a slightly higher pressure than that in the tank, along the tube, into the sight glass, and back to the tank. When the water level has been corrected, the solenoid valve closes until needed again.

This level control system was subject to numerous problems. Adjustment of the pressure differential between the tank and the forced air feed is critical, as is adjustment of the air flow rate. Impurities and foam in the recycle liquid tended to clog the sight glass, tube and the solenoid valve, and impair the functioning of the liquid sensor. No provision exists to correct a low-level condition in the tank. Because of these problems, the water in the tank is frequently not at the desired level. Eductor operation is impaired (see below), and the flotation operation can fail completely. As no mechanical solution was available, vigilant attention was required to maintain continuous operation.

Two other air control systems are available which may be preferable to the one used in the present study. Komline-Sanderson's 0.093 m^2 unit is equipped with a float system in a by-pass chamber outside the pressure tank. The float is mechanically linked to a mercury switch which triggers a solenoid valve when the water level is too high. An air stream then enters the tank directly and depresses the liquid level.

Another system uses two electrodes in the pressure tank to monitor the level and control the auxiliary air supply (Davis, 1977). This method would appear to be the simplest and most preferable, especially on small units where response time is critical.

In defense of the level control system used in this study, it is employed with apparent success in all full-scale installations at sewage treatment plants in Ontario. The response time in larger units is much longer than in pilot-scale plants, and for this reason the level control system is adequate. Nevertheless, where an option exists for an alternative method, either of those mentioned above might be preferable.

5.3.2 Eductor and Re-aeration System. In order to obtain adequate levels of air saturation, a re-aeration system is used. Liquid is pumped from the base of the pressure tank, and returned through one or more eductors. The turbulence thus created and the air forced into the liquid via the eductor mechanism are responsible for almost all the air that is forced into solution.

Only one eductor was supplied in the unit used for this study. The focal point of this eductor is an 8-mm nozzle through which the liquid is forced. The potential for

clogging is high and, once this occurs, air saturation drops, the pressure tank has to be opened, and the eductor removed and cleaned.

A simple method for cleaning the eductor during plant operation, requiring only minor pipe changes was devised. The piping configuration and cleaning method is shown in Figure 8.

5.3.3 Recycle Control Valve. The problem of hair, lint, and other contaminants occurred again in the recycle control valve. To maintain a steady supply of air for flotation, a constant recycle flow rate was required. After many changes, it was found that blockages could be avoided and a constant flow maintained by using a diaphragm valve. A 19-mm diaphragm valve proved to be more effective than the larger size and, provided it was flushed regularly, blockages and flow disturbances were minimized. The small opening had the added advantage of creating a head-loss high enough to ensure sufficient flow past the DO membrane in the line by-passing the control valve. However, recycle flow was thereby limited to 173 L/min.

5.3.4 Polymer Addition. Polymer in micro-bead form was mixed as a 0.1% solution and fed to the recycle line. This particular concentration is, according to the manufacturer, Allied Colloids, the weakest that can be stored for an extended period (i.e., 24 hours) and the strongest which can be added directly to the DAF system. It was necessary, therefore, to prepare this polymer on a daily basis.

A preferable system, and one in general use at full-scale installations, is to prepare a more concentrated polymer solution, say one percent, and feed it with dilution water via an in-line mixing arrangement. In this way, polymer can be stored in liquid form for longer periods and need not be prepared every day. This method was not feasible on the pilot scale unit.

5.3.5 Dissolved Oxygen Measurement. The air available for flotation was calculated from DO measurements obtained with a probe in a line by-passing the recycle control valve. It was hoped that DO readings could be taken continuously, but the fragile Teflon membrane on the probe was too easily ruptured by the solid impurities in the recycle liquid. Furthermore, it was found that readings would fall if the probe were subjected to a combination of high flow (up to 50 L/min) and elevated pressure (up to 138 kPa) for longer than about 1/2 hour. Periodically obtaining a value for the mass of air available for flotation was practical and easily done, but the equipment had to be handled with care, and the probe had to be cleaned and recharged regularly.

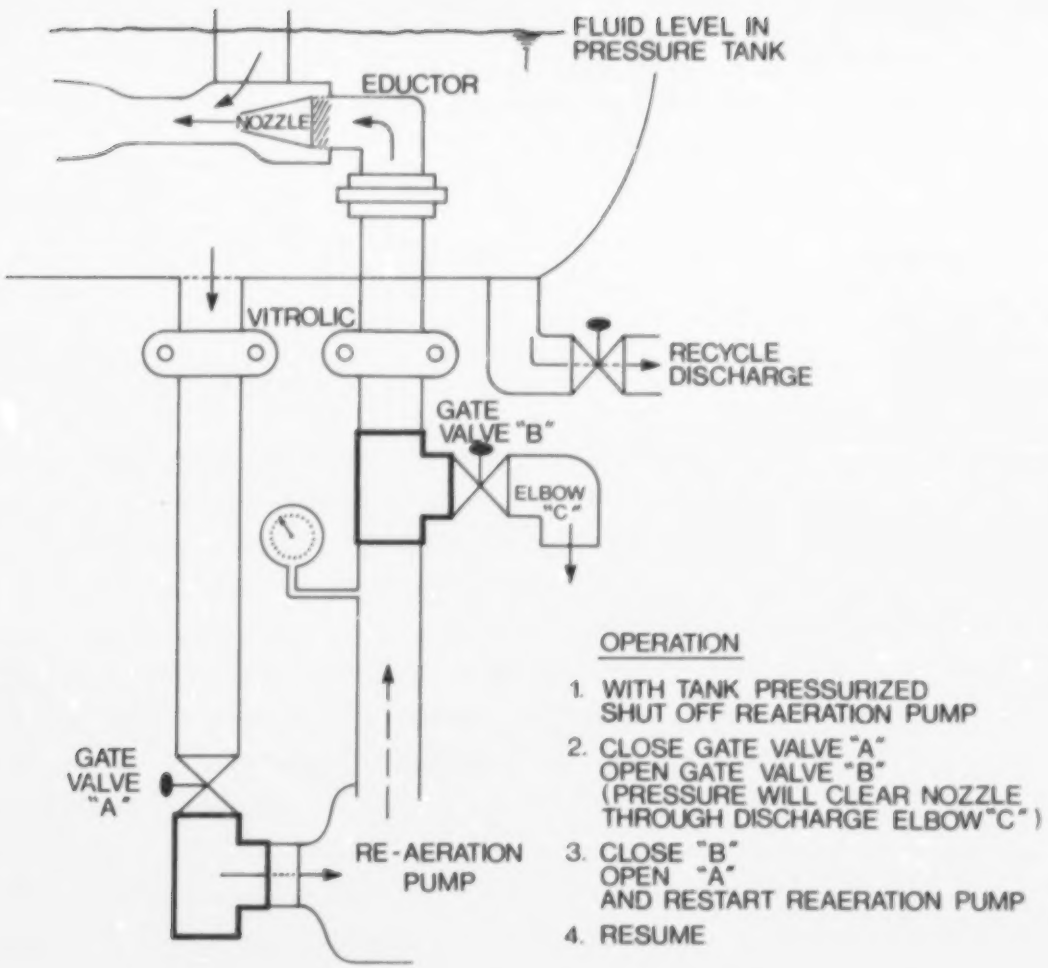

FIGURE 8 VALVE ARRANGEMENT FOR EDUCTOR CLEANOUT DAF PILOT PLANT

5.3.6 Skimmer Operation. The skimmer mechanism had a fixed speed drive, but the frequency of operation could be controlled by an automatic timer. This method for controlling the float removal rate was adequate in this case, but a variable speed drive would provide additional flexibility.

Operation of the skimmer was adequate provided the chain was correctly tensioned and regularly lubricated. In addition, the skimmer blades had to be adjusted to minimize underflow between the blade and the beeching plate. It was necessary to raise the beeching plate by adding a 6-mm PVC sheet because the skimmer blades could not be located closely enough to the original beeching surface.

5.3.7 Removal of Sludge Accumulations. Accumulations of sludge occurred wherever the skimmer blades changed direction of travel, and also at specific skimmer scraping points. Removal of these accumulations formed part of the regular maintenance routine.

5.4 Pilot Plant Results

5.4.1 General Comments. Pilot plant results for phase 1 are presented in Table 14. As mentioned in Section 4.3.2, only a limited number of tests were conducted. Furthermore, since these experiments were the first ones to be performed in the study, a number of problems relating to experimental technique were solved only as the actual run progressed, and the quality of data is not as high as that obtained in the other phases.

The recycle ratio exhibited considerable variation. Part of this was intentional, but part was also due to clogging of the recycle control valve; this valve was replaced during the course of the tests as described in Section 5.3.3.

In many cases, the air saturation is listed as 60 percent. This is an assumed value (based on experience) used when problems were experienced with the DO probe.

Influent samples were taken by automatic sampler from the rapid-mix tank. Where $FeCl_3$ was added, the value obtained for influent soluble phosphorus would obviously be affected by this addition which occurred before the rapid-mix tank. Therefore, an average value of 1.6 mg/L, calculated from the tests without $FeCl_3$, was used as an indication of influent soluble phosphorus.

5.4.2 A/S Variation. Figure 9 shows the variation of float solids with A/S. There is only one datum point for A/S below 0.024 without $FeCl_3$, and at this condition float solids show a definite drop. Above A/S 0.024, however, there is little change of float solids

TABLE 14 OPERATING RESULTS. DAF PILOT PLANT PHASE I

Test	Polymer dose (mg/g)	$FeCl_3$ dose (mg/g)	Recycle ratio	Air sat (%)	A/S x 100	Influent			Effluent		Float		Soluble P reduction (%)
						Flow (L/min)	SS (mg/L)	Sol P (mg/L)	SS (mg/L)	Sol P (mg/L)	TS (%)	TP	
1	1.01	0	2.5	68	3.81	32	4071	1.3	5	0.8	3.77	857	54
2	0.88	0	2.4	67	3.22	32	4651	1.1	8	-	4.00	915	36
3	0.93	0	2.6	63	3.22	32	4387	1.3	4	1.1	3.80	963	54
4	0.90	0	2.6	60	2.90	32	4552	1.7	12	-	3.75	1035	neg
5	1.13	0	2.3	60	2.54	32	4495	1.8	2	1.9	3.91	1111	neg
6	0.89	0	3.1	60	3.34	32	4605	1.8	14	2.1	4.25	1146	neg
7	0.93	0	2.1	60	2.58	32	4385	1.3	4	-	3.89	1427	neg
8	0.91	0	0.9	60	1.02	32	4476	-	10	2.1	2.55	1040	56
9	0.89	0	3.4	46	2.75	32	4572	1.7	8	2.2	4.07	1432	neg
10	0.84	0	4.2	52	3.19	32	4785	1.9	5	-	4.03	1362	neg
11	0.91	0	2.5	62	2.94	32	4508	1.1	10	2.9	3.39	895	neg
12	0.89	0	2.4	60	2.65	32	4582	1.7	3	1.2	3.89	1096	6
13	0.84	15	2.5	64	2.89	32	4872	1.6	11	0.4	3.73	926	75
14	0.83	15	2.1	65	2.49	32	4904	1.6	17	0.2	3.26	840	87.50
15	0.84	30	2.3	61	2.42	32	4880	1.6	6	0.6	3.65	1018	62.5
16	0.90	30	1.2	51	1.42	32	4553	1.6	5	1.1	1.83	626	31
17	0.86	45	2.5	65	3.00	32	4730	1.6	10	1.6	4.16	1027	0
18	0.87	60	2.5	60	2.60	32	4716	1.6	4	1.2	3.64	1038	25
19	0.91	60	2.5	60	2.91	32	4497	1.6	8	0.7	3.65	977	56
20	0.87	60	2.4	60	2.78	32	4679	1.6	4	0.4	3.43	907	75
21	0.42	60	1.6	60	1.94	32	4497	1.6	5	0.6	2.77	818	62.5
22	0.53	60	1.8	49	1.20	55	5572	1.6	5	1.0	3.51	1444	37.5

concentration with increasing A/S. A conservative A/S operating value of 0.028 should ensure adequate performance.

No graph of effluent solids concentration vs. A/S is presented because the accuracy of the measurements at such low levels (average 6 mg/L) is questionable.

When effective times thickening vs. A/S is plotted (Figure 10), only fair linear correlation is obtained (0.76), and the slope of 919 is significantly different from the average thickening parameter of 1106. This scatter of results is thought to be due to experimental errors.

5.4.3 Chemical Addition. From the results presented in Figures 9 and 10, it is evident that chemical addition had a little effect on performance. Reduced scatter is attributed to improved experimental technique rather than on more stable performance. In this case, the slope of the effective times thickening vs. A/S graph is statistically equal to the thickening parameter at the five percent confidence level (slope = 973; TP = 962).

5.4.4 Comparison of Performance With and Without $FeCl_3$. Table 15 below shows that $FeCl_3$ addition had minimal effect on flotation of mixed liquor from the extended aeration plant.

TABLE 15 FLOTATION PERFORMANCE, WITH AND WITHOUT $FeCl_3$. DAF PILOT PLANT PHASE 1

	Average Float TS (%)	Average Effluent SS (mg/L)	Average TP
without $FeCl_3$	3.9	6	1106
with $FeCl_3$	3.6	8	962

5.4.5 Extremes. Two tests (21 and 22) were purposely performed at "extreme" values: the first at a low polymer dose, and the second at low polymer dose, low A/S, and high hydraulic and solids load. No deterioration in performance was evident. Effluent SS was lower than the average for all the previous tests. Although float TS did drop in test 21, it rose again in test 22, and this effect is probably due to a thicker float blanket. In the second case, however, the high flow rate was sustained for only four hours, and although at the end of this period the performance had not deteriorated, it cannot be assumed that this high load could be handled on a sustained basis. Table 16 below shows

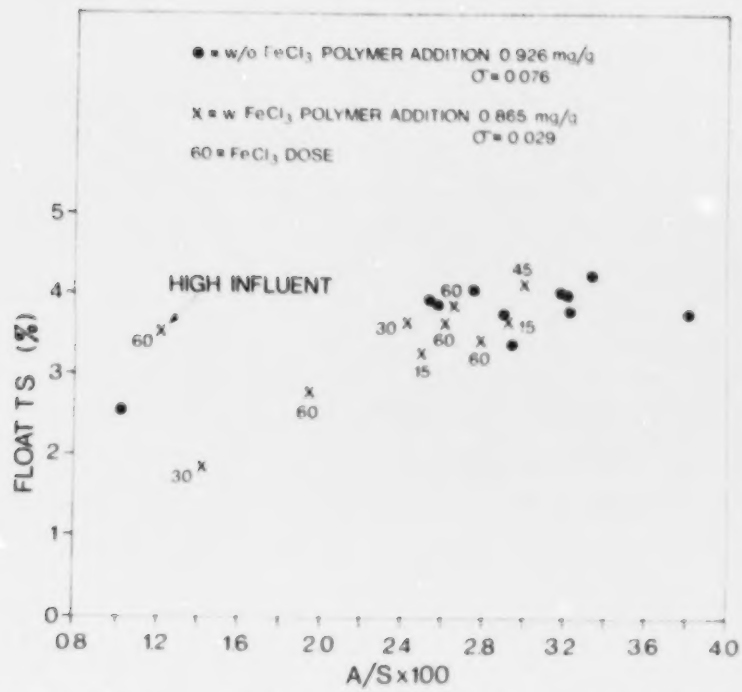
● = w/o FeCl3 POLYMER ADDITION 0.926 mg/g
σ = 0.076
X = w FeCl3 POLYMER ADDITION 0.865 mg/g
σ = 0.029
60 = FeCl3 DOSE
HIGH INFLUENT
FLOAT TS (%)
A/S x100

FIGURE 9 FLOAT SOLIDS vs. A/S. DAF BATCH FLOTATION UNIT PHASE 1

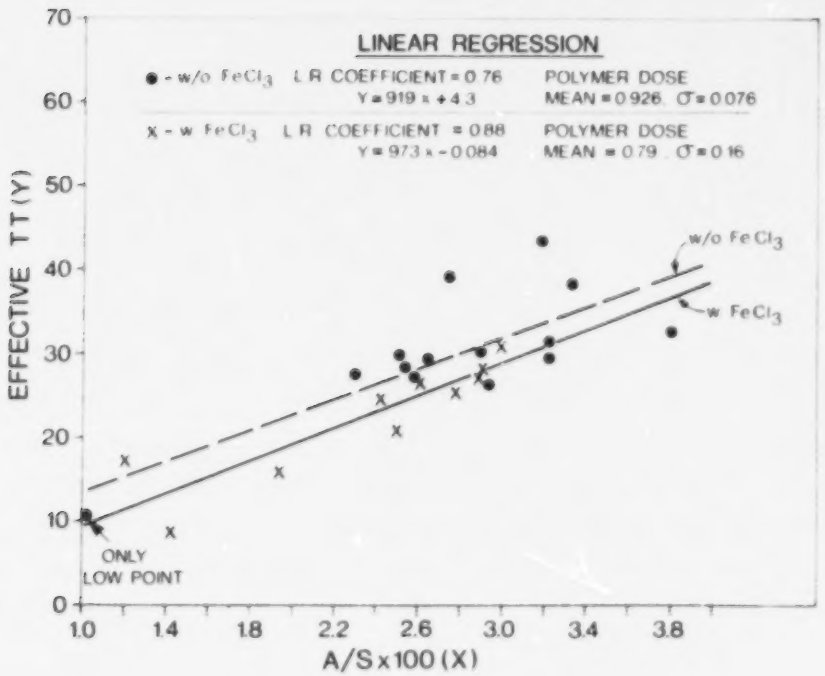
LINEAR REGRESSION
● - w/o FeCl3 L.R. COEFFICIENT = 0.76
Y = 919 x + 4.3
POLYMER DOSE
MEAN = 0.926 σ = 0.076
X - w FeCl3 L.R. COEFFICIENT = 0.88
Y = 973 x - 0.084
POLYMER DOSE
MEAN = 0.79 σ = 0.16
w/o FeCl3
w FeCl3
ONLY LOW POINT
EFFECTIVE T T (Y)
A/S x100 (X)

FIGURE 10 EFFECTIVE TIMES THICKENING vs. A/S, WITH ALL DATA POINTS. DAF PILOT PLANT PHASE 1

TABLE 16 RECOMMENDED, AVERAGE AND EXTREME OPERATING CONDITIONS AND TEST RESULTS. DAF PILOT PLANT PHASE 1

	Polymer Dose (mg/g)	Air Sat. (%)	A/S x 100	Influent Flow (L/min)	SS (mg/L)	Hydr. Load (m/h)	Solids Loading ($kg/m^2 \cdot h$)
Recommended by Manufacturer	-	75-95	-	-	-	1.95	9.8
Average, tests 1-20	0.90	60	2.73	32	4600	2.27	10.4
Test 21	0.42	60	1.94	32	4500	2.27	10.3
Test 22	0.53	49	1.20	55	5572	3.90	21.8

the average and extreme operating conditions and test results, and the operating levels recommended by the manufacturer.

No tests were conducted in this phase specifically to determine whether the DAF unit could operate without polymer. During the experiments, polymer addition was inadvertently briefly suspended and effluent quality deteriorated markedly.

5.4.6 Summary of Operating Values and Test Results. Once again, the average operating values given in Table 17 were obtained from a relatively small number of tests with a limited range of imposed conditions. The loading parameters may be considered conservative. Indications were that the plant could be stressed to as much as twice the values suggested without deterioration in performance.

TABLE 17 FLOTATION OF EXTENDED AERATION MIXED LIQUOR. DAF PILOT PLANT PHASE 1

Parameter	Average Value
Inflow (L/min)	32
Influent SS (mg/L)	4600
Polymer (mg/g)	0.9
$FeCl_3$ (mg/L)	0-60
Air (Sat. %)	60
A/S Ratio	0.028
Hydraulic Load (m/h)	2.27
Solids Load ($kg/m \cdot h$)	10.4
Effluent SS (mg/L)	< 10
Float TS (%)	3.8
TP	1000

5.5 Scale-Up

Table 18 compares batch and pilot plant performance. In general, performance was comparable, with the only significant difference being that the pilot plant effluent quality showed as much as a four-fold improvement.

TABLE 18 COMPARISON OF BATCH AND PILOT PLANT PERFORMANCE, PHASE 1

		Batch DAF	Pilot Plant DAF
Pressure (kPa)		207-345	386 average
Optimum A/S		0.02 A/S had small linear effect on float solids.	0.028 Above 0.024 A/S had no clear effect on float solids.
Polymer dose (mg/g)		0.7-0.9	0.93 average
Float TS (%)	No polymer	4.2	
	Polymer only	4.0	3.9
	Polymer + $FeCl_3$	4.0	3.6
Effluent SS (mg/L)	No polymer	47	-
	Polymer only	14	6
	Polymer + $FeCl_3$	35	8
TE*	No polymer	y = 809 x +5.1	-
	Polymer only	y = 1037 x -1.1	y = 919 x +4.3
Mean TP	No polymer	1154	-
	Polymer only	969	1106
	Polymer + $FeCl_3$	1107	962
Effect on $FeCl_3$ addition		Increased effluent solids	Minimal

* Thickening equation.

The quality of the pilot plant data is poorer than would be hoped for because of the paucity of experiments and the earlier lack of reliable experimental technique. Thus, slight differences between batch and pilot plant results (e.g., float solids with polymer and $FeCl_3$ addition of 4.0 percent and 3.6 percent, respectively) can be disregarded. The comparison between thickening equation slope and TP for the two units, and the variation of these parameters when $FeCl_3$ is, or is not, present is not entirely

understood. However, the overall differences were small enough that, once an overall value of 1000 for the TP had been established (by batch or pilot studies) for a particular waste, it could be used to assess the effectiveness of different polymers in flotation and the dosage required. Air requirements, and the related recirculation ratio, could also be determined.

In general, the batch tests in phase 1 were a reliable indication of pilot plant performance, except for effluent solids, where the pilot plant yielded superior results. However, since the batch unit is by definition a discontinuous system, it cannot produce design values for continuous parameters such as solids and hydraulic loading; these would still have to be evaluated by means of a continuous system. Application of the thickening parameter and thickening equation to assess DAF performance is discussed in more detail in Appendix E.

5.6 Economics for Flotation of Mixed Liquor in Extended Aeration

Air flotation of mixed liquor (@ 4600 mg/L) from an extended aeration process produced a float of approximately four percent solids concentration. Sedimentation of the same effluent would produce about a one percent float. To compare DAF and sedimentation on an equitable basis (i.e., equal thickening) the one percent sludge from the settling tank must be further concentrated. Flotation thickening is now widely used for this purpose and its cost was, therefore, added to the sedimentation costs for a realistic comparison with DAF.

Sizes of the units for the two alternatives were based on the governing hydraulic or solids loading as follows:

Alternative	Average Loading	Peak Loading Factor
1. DAF (Mixed Liquor)	2.27 m/h*	1.8
2. Sedimentation/Thickening		
a) Final Settling	0.61 m/h**	2
b) Flotation Thickening	9.8 kg/m^2***	2

* from the pilot data in phase 1
** current practice, Ontario Ministry of the Environment.
*** manufacturers' recommendations.

A detailed listing of all design criteria affecting costs is provided in Appendix K.

Costs for alternatives 1 and 2 above were estimated for extended aeration plants of 4500, 45 500 and 227 000 m^3/d capacity even though in practice, the two largest sizes would not likely utilize extended aeration.

Information from construction contracts provided by consulting engineers, and equipment prices supplied by manufacturers were used as the basis for estimating capital costs. Annual costs for power, labour, maintenance and chemicals, are typical of southern Ontario.

Appendix K includes details of cost estimates for excavation, concrete, equipment installation, etc., as well as the breakdown of operation and maintenance charges. Comparative costs for DAF and sedimentation in the extended aeration process are summarized in Table 19 below.

TABLE 19 COMPARATIVE COSTS: EXTENDED AERATION

	4500 m^3/d	45 500 m^3/d	227 000 m^3/d
Capital Costs			
1. DAF (Mixed Liquor)	$670 000	5 484 000	22 680 000
2. Sedimentation/Thickening			
a) Final Settling	172 000	1 313 000	5 752 000
b) Flotation Thickening	121 000	422 000	676 000
	$293 000	1 735 000	6 428 000
Operation & Maintenance Costs			
1. DAF* (Mixed Liquor)	69 600	587 000	3 310 000
2. Sedimentation/Thickening			
a) Final Settling	5 800	28 000	119 000
b) Flotation Thickening*	4 800	19 100	58 200
	$ 10 600	47 100	177 200

* Includes polymer costs

6 EXPERIMENTAL RESULTS AND DISCUSSION - PHASE 2 (RAW SEWAGE)

6.1 Jar Tests

The three sets of tests using alum, $FeCl_3$, and lime, respectively, did not yield conclusive results. This was a result of three factors: a wide variation in initial phosphorus concentration (2.6 - 5.6 mg/L total P; 1.5 - 3.0 mg/L total soluble P); a variation in the ratio between initial total P and total soluble P (1.7 - 2.4); and, the low precision of the analytical results at values below 1.0 mg/L. Since these jar tests were peripheral to the main study, replicates were not warranted, and $FeCl_3$ was again chosen as the phosphorus removal chemical. The reasons for this choice were similar to those in phase 1, i.e., $FeCl_3$ is in widespread use for phosphorus removal, and it appeared to be the most economical. Futhermore, it was desirable to maintain consistency between the phases, all other factors being equal.

6.2 Batch Flotation Tests

Solids concentrations in the raw sewage influent were so low (around 200 mg/L) that the volume of float obtained in the batch tests was too small for representative sampling. Hence, all conclusions drawn from the batch test experiments were based on effluent quality.

6.2.1 Determination of Optimum A/S. The effect of increasing A/S on effluent SS is shown on Figure 11. Contrary to previous experience with mixed liquor and waste activated sludge (Gehr and Henry, 1976) there is a clear improvement in effluent quality as A/S increases. The data are of the unstable-stable form, similar to those presented by Mulbarger and Huffman (1970). The stable zone where effluent quality becomes more consistent seems to extend from an A/S of approximately 0.3 onwards. In the later tests with mixed liquor and waste activated sludge, the authors found either no relationship at all between effluent SS and A/S or, surprisingly, a deterioration of effluent quality with increasing A/S.

Although it can be recommended, as a result of these batch tests, that an A/S of 0.3 be used with the pilot plant, the wide variation of SS concentration in the raw sewage makes it impossible to maintain a constant A/S. The aim in design should probably be to ensure that A/S does not drop below 0.3 even at the highest level of influent solids concentration.

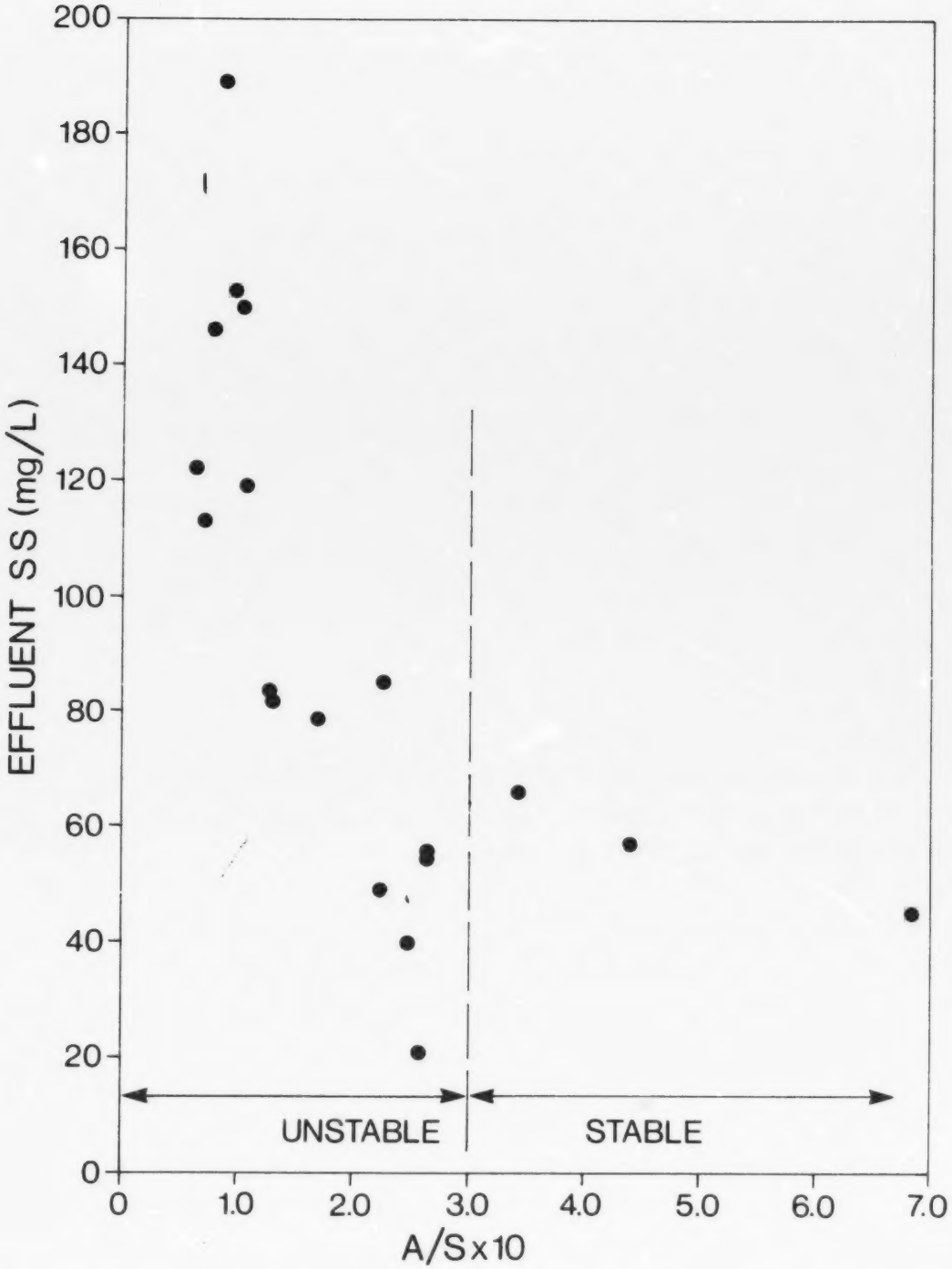

FIGURE 11 EFFLUENT SS vs. A/S. DAF BATCH FLOTATION UNIT. PHASE 2

6.2.2 Choice of Polymer. It could not be established from the 52 tests on 17 polymers which, if any, was the most suitable. Since Percol 757 had been used previously and was among the acceptable ones, it was used for the pilot plant tests.

6.2.3 Optimum Polymer Dose. Tests at various doses were performed with those polymers offering promising performance, and in many cases it was found that polymer addition in fact did not reduce effluent solids concentration. Tests on different samples using the same polymer yielded scattered results and, in some cases, the lowest concentration of effluent solids was obtained without any polymer at all. The 13 tests with Percol 757 also exhibited no specific trend, and it could not be said with certainty that addition of this polymer would improve performance (Table 20). Consequently, it was

TABLE 20 EFFECT OF POLYMER (PERCOL 757) ADDITION. DAF BATCH FLOTATION UNIT PHASE 2

Test	Polymer dose (mg/g)	Influent SS (mg/L)	A/S x 10	Effluent SS (mg/L)	Solids capture* (%)	Solids Reduction** (%)
1	4.07	231	2.63	46	61	80
2	0.38	183	2.60	69	36	62
3	1.50	183	2.29	45	58	75
4	3.00	183	2.35	13	88	93
5	4.50	183	2.28	62	42	66
6	0.85	161	2.61	43	55	73
7	2.56	161	2.36	43	55	73
8	4.27	161	-	39	59	76
9	6.00	161	2.68	41	57	75
Mean	3.01	178	2.47	45	57	75
σ	1.87	92	0.17	16	14	9
10	0.27	552	0.86	146	54	74
11	0.75	552	0.80	142	57	74
12	1.25	552	0.75	131	60	76
13	2.60	369	1.14	112	48	70
Mean	1.22	506	0.88	133	55	74
σ	1.00	92	0.17	15	5	3

$$*\text{Solids Capture} = \frac{\text{Total SS (Inf. + Recycle) - Eff. SS}}{\text{Total SS (Inf. + Recycle)}} \times 100$$

$$**\text{Solids Reduction} = \frac{\text{Influent SS - Effluent SS}}{\text{Influent SS}} \times 100$$

not possible to recommend a particular dosage, or even a range of doses, for pilot plant operation.

Since these tests were conducted over an extended period (20 days separating the first and last tests), the influent SS varied considerably. Table 20 is divided into two sections, comprising low and high influent SS. Since A/S and polymer dose are inversely proportional to influent SS, all other factors being equal, these quantities were proportionally lower for the latter set of tests (tests 10 to 13). Hence, the marked deterioration in effluent SS could be due to either A/S reduction, or polymer dose reduction, or both. Of significance, however, is the fact that neither mean solids capture nor mean solids reduction were affected, indicating that percent solids removal was not really affected by either A/S or polymer dose.

6.2.4 Comparison of Recycle Liquids. The purpose of these batch tests was to assess whether the choice of recycle liquid influenced the results. Previous tests on waste activated sludge (Gehr and Henry, 1976) had shown that, without polymer, results were the same whether tapwater or activated sludge effluent was used as recycle. However, with polymer, the solids in the activated sludge effluent recycle were flocculated in the pressure chamber by the polymer, and less polymer was available for flotation. In a continuous-flow DAF unit, polymer is introduced after pressurization and a polymer loss would not occur. For closer comparison between batch and continuous-flow units, tapwater had been used for recycle in the previous work.

In the current study, effluent from the DAF pilot plant was available for some tests performed to determine whether use of this effluent recycle would influence batch test results. If the influence was consistent and significant, then clearly the real recycle, i.e., the DAF effluent, should be used in the batch tests to more closely simulate pilot plant operation.

The results of eight tests are shown in Table 21. A problem arises in choosing which of three effluent parameters (effluent SS, solids capture, or solids reduction) should be used for comparison purposes. Solids reduction takes into account the SS in the influent, whereas solids capture also accounts for the solids in the recycle. However, especially when clarification is of prime concern, effluent SS would be the final measure of performance, and it is this quantity which has to be related to pilot plant DAF results.

The comparison is further complicated because polymer dose is calculated on a mass basis and is, therefore, affected by solids in the recycle. The dose will differ substantially for tapwater and DAF effluent recycle, even when the influent SS and

TABLE 21 COMPARISON OF RECYCLE LIQUIDS. DAF BATCH FLOTATION UNIT PHASE 2

Test	Polymer dose (mg/g)	Influent SS (mg/L)	Recycle SS (mg/L)	A/S Ratio	Effluent SS (mg/L)	Solids capture (%)	Solids reduction (%)
1	0	481	171	0.832	150	58	77
2	0	481	0	0.95	153	47	68
3	0	363	149	0.663	146	52	60
4	0	363	0	0.630	122	60	66
5	0.65	176	149	1.11	99	22	44
6	0.97	176	0	1.64	74	40	58
7	1.19	219	92	0.94	99	38	55
8	1.38	219	0	1.16	84	47	62

quantity of polymer added in each test are the same. In the tests with raw sewage, recycle SS was of the same order of magnitude as the influent SS, whereas in tests with activated sludge mixed liquor, the recycle SS would generally be two orders of magnitude lower, and would not significantly affect the effluent parameters and polymer dose.

The recycle test results were inconclusive. The tests without polymer (tests 1 to 4) gave conflicting results, with all three effluent parameters improving in the one case when DAF effluent was used as recycle, and deteriorating in the other. The differences were small, however. With polymer, all the effluent parameters deteriorated when DAF effluent was used for recycle, but this deterioration could have been due to the lower effective polymer dose.

It was decided, on the basis of the tests, that DAF effluent should be used as recycle in the batch unit, whenever possible; at worst, the results obtained would be conservative. However, this effluent could be used only when polymer was not being added to the pilot plant because it was likely that polymer would then be present in the effluent and could substantially affect the batch test results.

6.2.5 $FeCl_3$ vs. Alum Addition (no polymer). Tests 1 to 8 in Table 22 show the effects of $FeCl_3$ and alum addition on batch flotation. Although effluent SS is the most important basis for comparison, solids capture does take into account the effect of recycle SS. This effect will be significant when recycle SS is relatively high compared to influent SS as, for example, in tests 2 and 6.

TABLE 22 EFFECTS OF $FeCl_3$ AND ALUM ADDITION ON FLOTATION. DAF BATCH FLOTATION UNIT PHASE 2

Test	Chemical	Dose (mg/L)	Influent SS (mg/L)	Influent Sol P (mg/L)	Recycle SS (mg/L)	A/S x 10	Effluent SS (mg/L)	Effluent Sol P (mg/L)	Solids Capture (%)	Solids Reduction (%)	Soluble P Reduction (%)
1	$FeCl_3$	10	187	-	63	2.03	22	-	84	88	-
2		25	108	-	63	3.04	29	-	68	73	-
3		25	195	-	107	1.84	64	-	78	67	-
4		40	217	-	143	1.42	68	-	64	69	-
5	Alum	40	187	-	63	2.02	22	-	84	88	-
6		50	108	-	63	3.10	31	-	65	71	-
7		100	195	-	107	1.86	81	-	72	58	-
8		160	217	-	143	1.52	74	-	60	66	-
9		0	177	3.3	-	2.61	55	2.9	47	69	12
10	$FeCl_3$	15	177	3.3	-	2.35	38	2.5	64	79	24
11		30	177	3.3	-	2.41	47	2.4	56	74	27

Other factors being equal, effluent quality appears to deteriorate as the chemical dose is increased. The most useful comparison is between tests 1 and 3 for $FeCl_3$ addition, and tests 5 and 7 for alum addition, because the influent SS and A/S ratio remained virtually constant. The results indicate that excessively high doses do cause effluent deterioration; however, similar results are obtained when the alum dose is up to four times higher than $FeCl_3$.

Three additional tests (9 to 11) were done using $FeCl_3$ only in the same influent sample, with a virtually constant A/S ratio. These tests confirmed that a small dose of $FeCl_3$ is beneficial for solids removal, but that overdosing causes the effluent SS to increase again. The critical point was at approximately 15 mg/L $FeCl_3$, but this dose is likely to depend on the influent SS as well as the influent concentration of soluble phosphorus.

6.2.6 $FeCl_3$/Percol 757 Interaction. The purpose of this set of tests was to determine whether the combination of $FeCl_3$ and polymer (Percol 757) addition would have a beneficial effect on solids removal, compared to polymer dosing alone. Table 23 shows the results.

TABLE 23 COMBINATION OF CHEMICAL AND POLYMER ADDITION. DAF BATCH FLOTATION UNIT PHASE 2

Test	Chemical Dose (mg/L)	Polymer Dose (mg/g)	Influent SS (mg/L)	Recycle SS (mg/L)	A/S x 10	Effluent SS (mg/L)	Solids Capture (%)	Solids Reduction (%)
1	25	0.59	191	63	1.98	35	75	82
2	25	1.76	191	63	1.99	34	75	82
3	25	1.57	305	193	1.03	113	56	63
4	25	2.20	305	193	1.04	91	65	70

It was again impossible to obtain a feed with constant solids concentration and both A/S ratio and polymer dose varied widely.

The results in Table 20 and 23 for the single vs. dual additions are best compared using solids capture, because the solids mass in the DAF effluent used as recycle liquid in the latter case is accounted for. The DAF effluent was used as recycle in the tests with $FeCl_3$ because it was considered preferable to use a recycle liquid similar or equal in phosphorus content to that of the DAF pilot plant. As discussed in

section 6.2.4, the two different recycle liquids should not affect the results in terms of flotation performance. The results can, therefore, be considered to illustrate the effects of the additions only.

Because the influent SS concentrations were similar, the mean values in the first nine tests shown in Table 20 should be compared with tests 1 and 2 in Table 23, and the mean values in the remaining tests in Table 20 with tests 3 and 4 in Table 23. In both cases, solids capture improved when both $FeCl_3$ and polymer were added; in fact, even the effluent itself showed an improvement, notwithstanding the fact that the recycle in the second set of tests also contained solids. It can be concluded that improved performance can be achieved when a suitable combination of both polymer and $FeCl_3$ are added to the influent raw sewage.

6.3 Pilot Plant Operation

Surprisingly few operating problems were encountered during the pilot phase of the study. Because of the small particle size and the non-flocculating nature of raw sewage, line blockages were not as frequent as was the case with activated sludge mixed liquor, and general operation was simpler and smoother.

The only major problem was the amount of hair and lint in the influent. These tended to accumulate on the stirrers of the rapid-mix and flocculating tanks, and on any protrusions in the piping. All unnecessary valves were removed from the lines, and daily cleaning of the stirrer blades prevented slugs of hair from reaching the DAF unit. With regular eductor clean-out, no problems were experienced with the re-aeration system.

6.4 Pilot Plant Results

6.4.1 Introduction. The results of the 72 pilot plant experiments conducted are presented in Appendix H.

The wide scatter of values for influent SS presented problems in the data analysis. After many attempts at graphical and statistical representations and analysis, the following three methods were used:

a) Graph of Effluent SS vs. A/S. - In each of the four sets of experimental conditions, this plot was of the form unstable-stable.

b) Probability plots of influent and effluent total phosphorus and SS. - The data are presented in the form of a cumulative probability plot indicating what percentage of tests yielded results below the indicated value. The probability scale was normal, requiring that the data be drawn from a normally-distributed population. A package

computer program used to test the entire set of values for influent SS yielded the following results:

- The null hypothesis that the variation in influent SS was normally distributed was accepted at the 0.05 level of significance.
- Number of Samples 71
- Mean SS 216.3 mg/L
- Skewness 0.83
- Standard deviation 103.5
- Kurtosis 3.72
- Range of standard deviation 5.26

Thus, although the null hypothesis was accepted at the five percent level, the distribution is actually positively skewed and of Leptokurtic form. This divergence from ideal normality is also evident in the probability plots for each section where, since the samples are smaller, the divergence is more marked. Nevertheless, for lack of any other useful data analysis technique, this probability plotting method is used here for comparative purposes.

c) Plot of effective times thickening vs. A/S, and comparison of the slope of this graph with the thickening parameter. - Since the TP itself varied over a considerable range, a cumulative probability plot of this parameter was also obtained.

Other plots, such as effluent SS vs. solids load, revealed no observable trend over the range of experiments. However, effluent SS did show a marked increase when the influent SS concentrations were abnormally high. In these cases, A/S ratio and polymer dose in mg/g always dropped correspondingly. Thus it may be suggested that the solids load parameter, for example, would not be related to effluent SS over the range tried in these experiments, provided sufficient air, and possibly polymer, were provided to allow A/S and polymer dose to remain at the desired operating level.

6.4.2 Effluent SS vs. A/S. Figures 12, 13, 14 and 15 show the effect of A/S on effluent SS for the four sets of experimental conditions. In each case, there appears to be a desirable A/S above which (except for one result shown on Figure 15) a low and stable effluent SS concentration will be obtained. Table 24 shows the A/S and stable (upper) levels of effluent SS obtained for the four conditions. The point where change occurs has been visually selected and seems to range between an A/S of 0.2 to 0.4, as indicated by the arbitrary delineation on Figures 12 to 15.

A suitable combination of polymer and $FeCl_3$ addition appears to produce the best effluent. However, the low value for effluent SS derives from one test only, and no

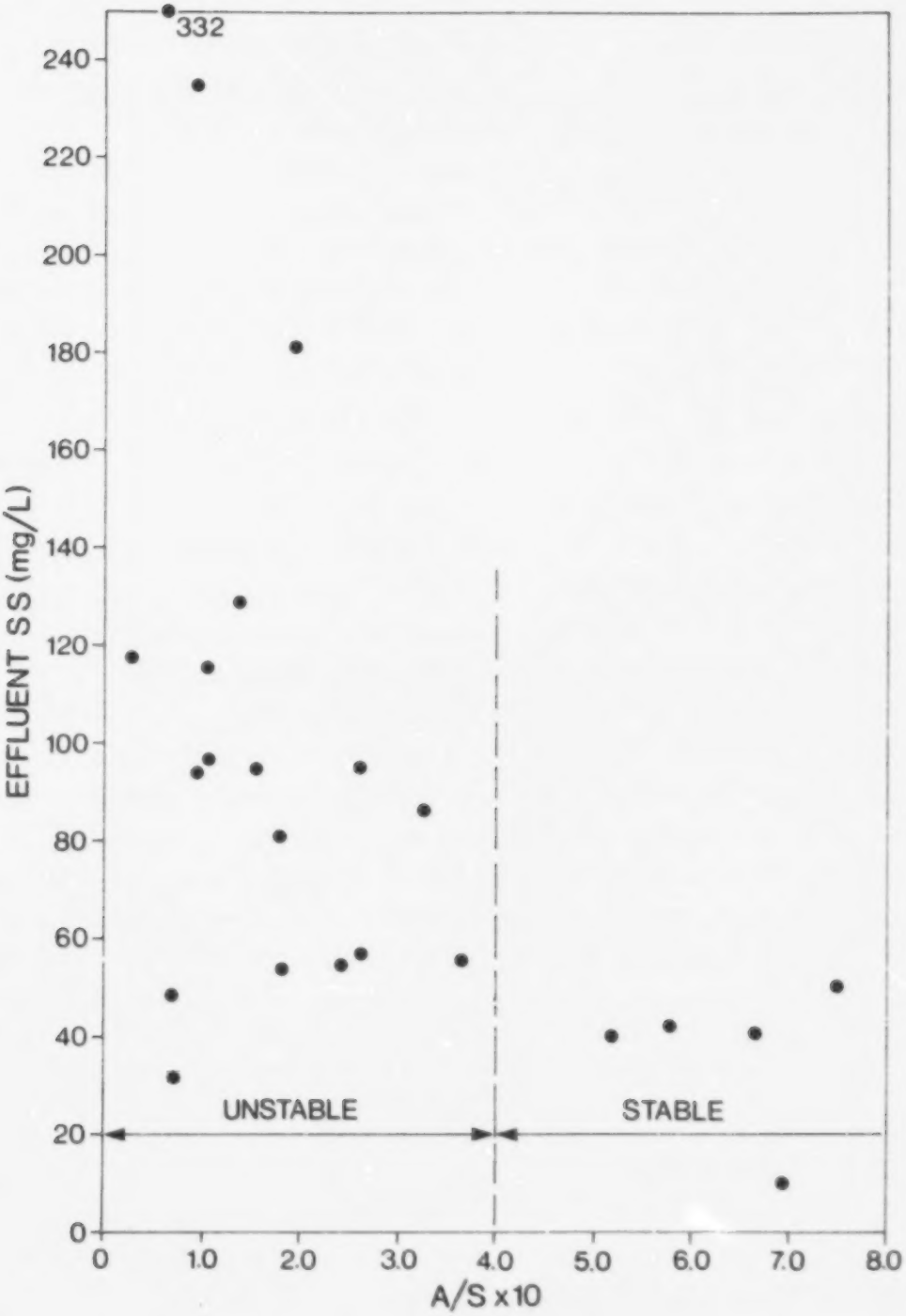

FIGURE 12 EFFLUENT SS vs. A/S NO ADDITIONS. DAF PILOT PLANT. PHASE 2

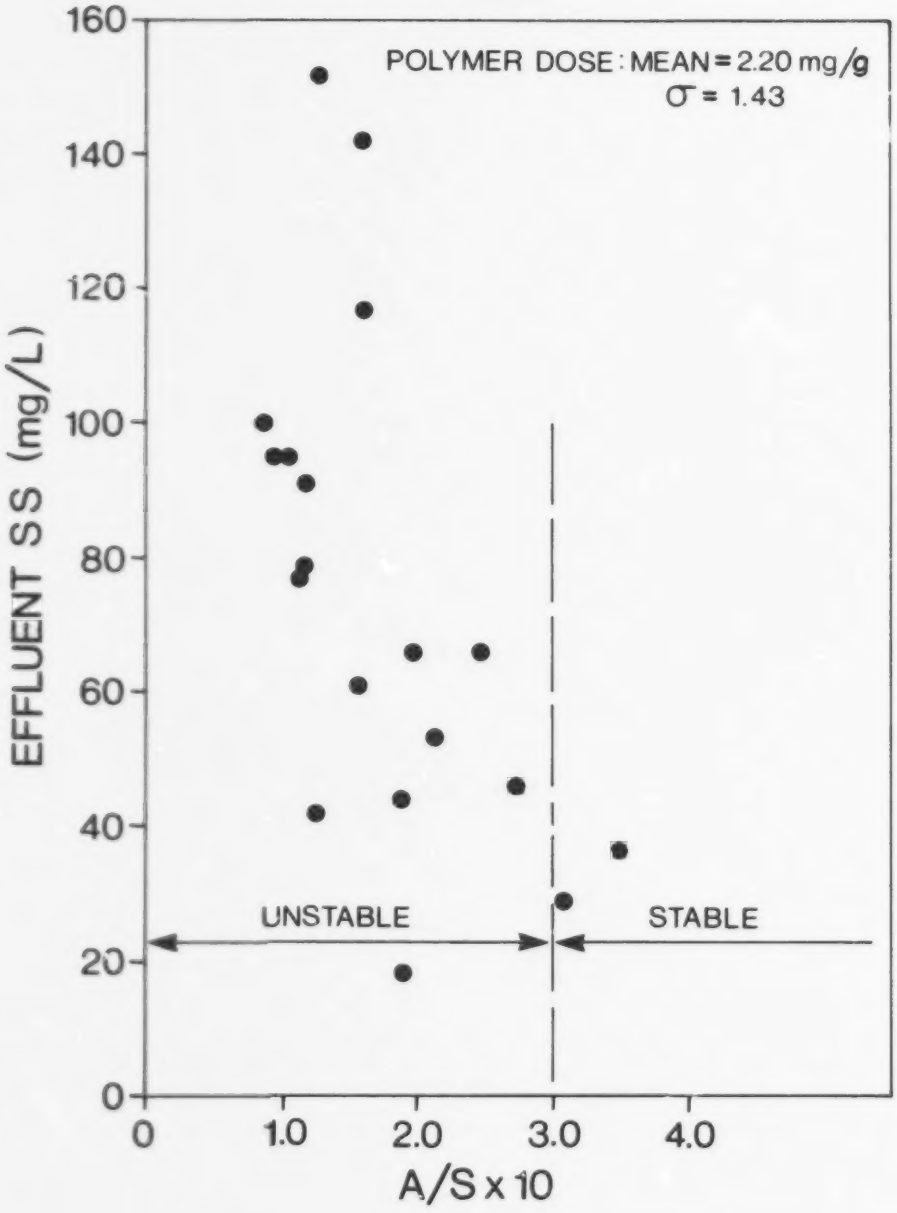

FIGURE 13 EFFLUENT SS vs. A/S, WITH POLYMER ADDITION. DAF PILOT PLANT. PHASE 2

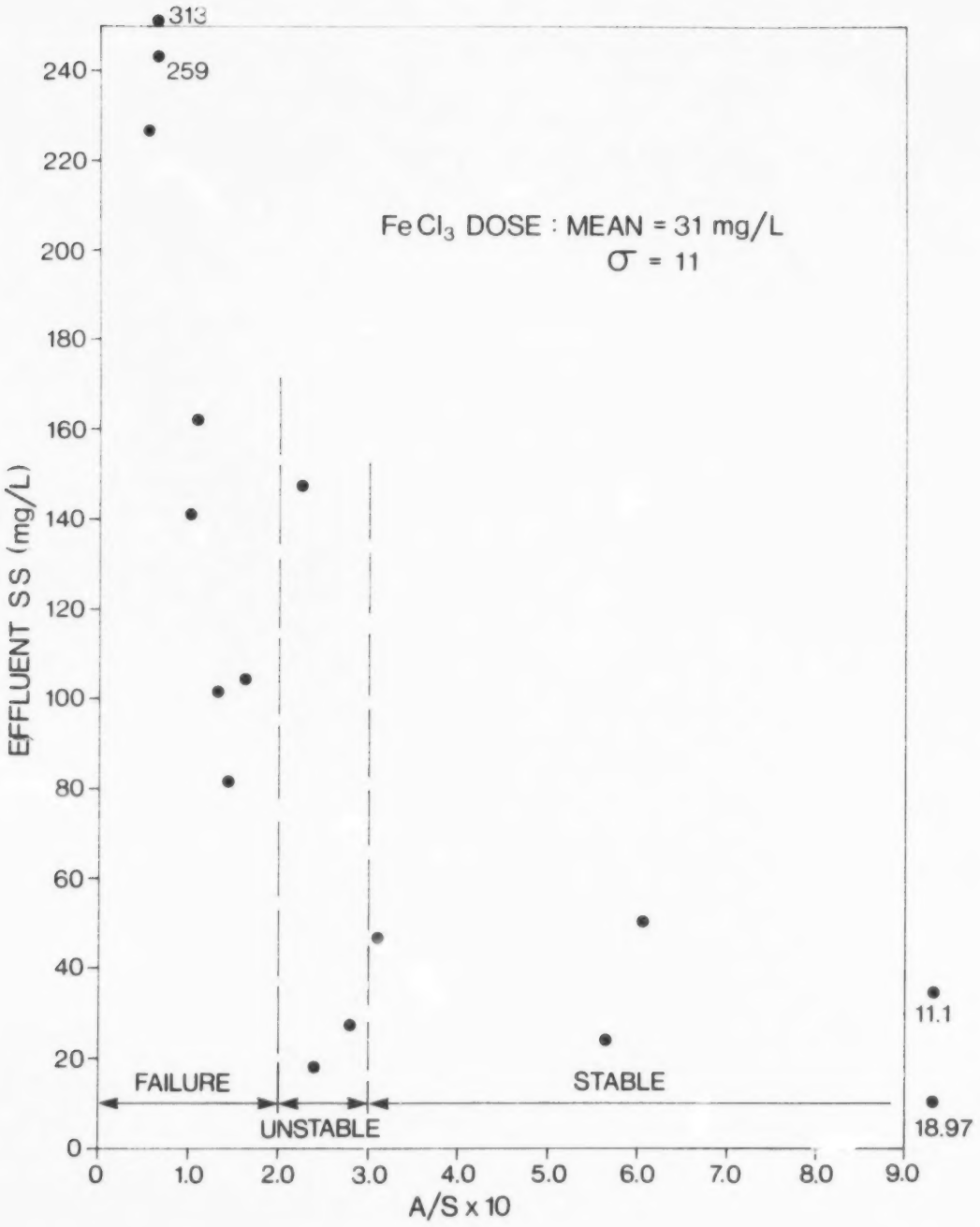

FIGURE 14 EFFLUENT SS vs. A/S, WITH $FeCl_3$ ADDITION. DAF PILOT PLANT. PHASE 2

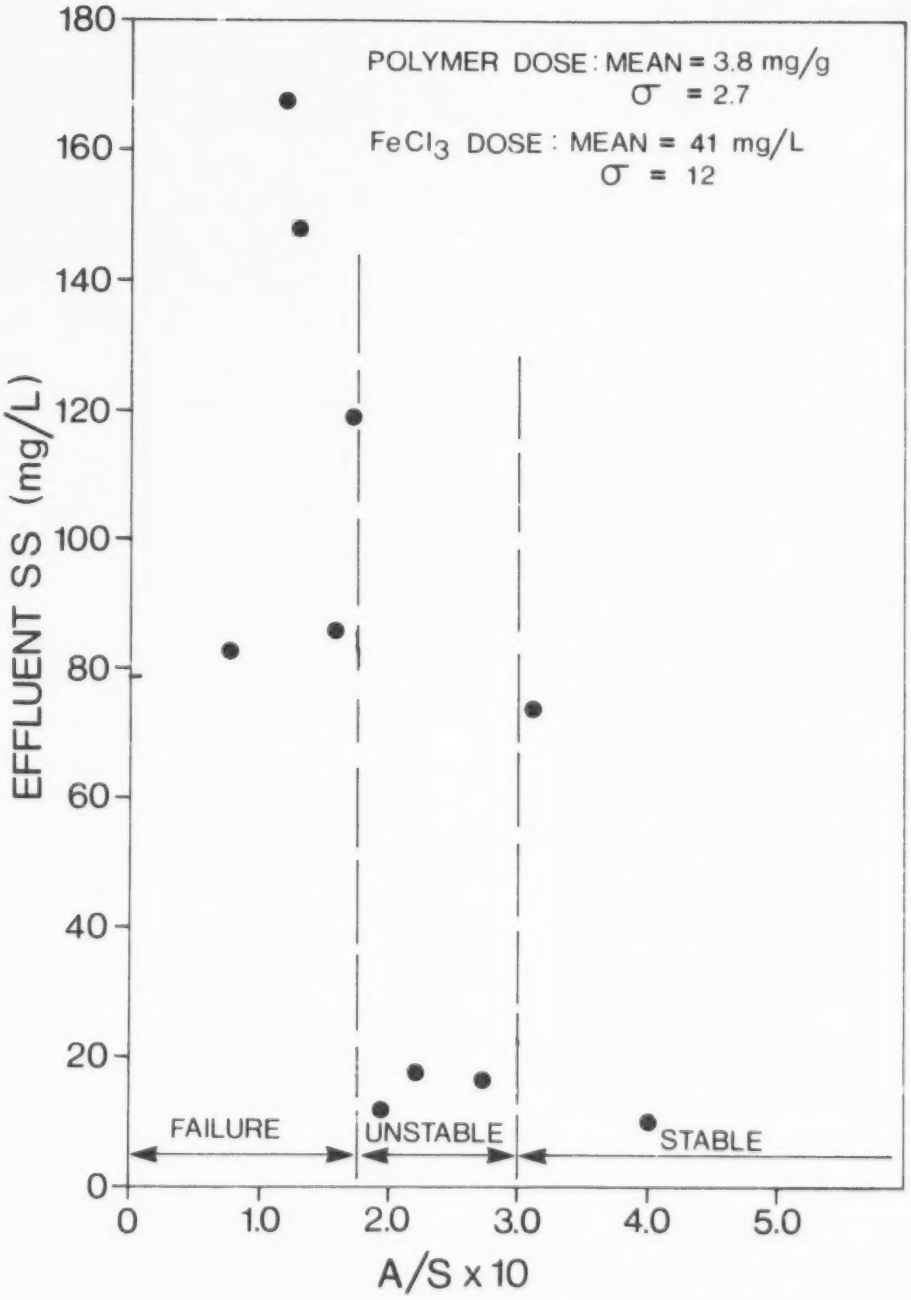

FIGURE 15 EFFLUENT SS vs. A/S, WITH POLYMER AND $FeCl_3$ ADDITION. DAF PILOT PLANT. PHASE 2

TABLE 24 MINIMUM A/S RATIO FOR STABLE EFFLUENT SS FOR FOUR EXPERIMENTAL SETS. DAF PILOT PLANT PHASE 2

Experimental set	Figure	A/S	Maximum Stable Effluent SS Obtained (mg/L)
1) No additions	12	>0.4	50
2) Polymer addition (mean 2.2 mg/g)	13	>0.3	40
3) $FeCl_3$ addition (mean 31 mg/L)	14	>0.3	50
4) Polymer and $FeCl_3$ addition (mean 3.8 mg/g and 41 mg/L)	15	>0.35	20

definite conclusion should be drawn. In terms of cost effectiveness, it is likely that operation without polymer producing slightly lower quality effluent at a 33 percent higher A/S would be preferable to two additions. However, no indication of process stability for overloaded conditions is evident in Table 24.

6.4.3 Influent and Effluent Total P and SS. A summary of 50 percent and 90 percent probability values is given in Table 25.

a) Total P Removal - Using 50 percent as an estimate of the mean, the best percentage reduction in total phosphorus was obtained when $FeCl_3$ and polymer were used together. The 90 percent value may be regarded as indicating performance at extreme conditions. As might be expected, total P removal is closely allied to SS removal.

b) SS Removal - At the 50 percent probability point, i.e., the average value, addition of only $FeCl_3$ gave the worst performance, and polymer addition alone yielded the best. $FeCl_3$ addition generally appears to be slightly detrimental to SS removal, as shown by the 90 percent value (Table 25). Polymer addition alone provided the best stability in terms of consistent removal. This stability is borne out by the removal at the worst condition, i.e., at the 95 percent probability value. The SS value that would occur in 95 percent of all tests conducted would be less than 25 mg/L, when $FeCl_3$ and polymer are added. Removal is also good at the highest probability level, but there are insufficient data to draw definite conclusions.

In summary, the probability values show that polymer addition alone gives the most stable performance in terms of both total P and SS removal. This conclusion does

TABLE 25 SUMMARY OF PROBABILITIES FOR TOTAL P AND SS REMOVALS IN RAW SEWAGE. DAF PILOT PLANT, PHASE 2

	Total P (mg/L)		Suspended Solids (mg/L)	
	% Probability		% Probability	
	50	90	50	90
No additions				
Influent	4.4	8.8	230	390
Effluent	4.4	5.6	80	200
% Reduction	0	36	65	49
Polymer addition(1)				
Influent	6.5	8.8	220	370
Effluent	4.3	5.6	70	150
% Reduction	34	36	68	59
$FeCl_3$ addition(2)				
Influent	3.1	7.8	140	330
Effluent	1.9	6.8	80	220
% Reduction	39	13	43	33
Polymer and $FeCl_3$ addition(3)				
Influent	3.0	5.6	170	360
Effluent	1.4	5.4	80	160
% Reduction	53	3	53	55

(1) Mean doses: 2.19 mg/g; σ = 1.43 mg/g
(2) Mean doses: 30 mg/L; σ = 10 mg/L
(3) Mean doses: 3.84 mg/g and 41 mg/L; σ= 2.68 mg/g and 12 mg/L (polymer and $FeCl_3$, respectively)

not suggest that $FeCl_3$ would not be desirable for soluble P removal; in fact, previous experience suggests that polymer itself would not remove soluble phosphorus. It should also be noted that the probability values do not take into account variations of A/S and polymer dose (calculated on a mass basis). Furthermore, the difference in SS removal between the cases of no addition and polymer addition is not great enough to state

categorically that polymer addition is necessary. As pointed out earlier, polymer could likely be excluded on an economic basis and a certain level of effluent deterioration tolerated when the system is shock loaded.

6.4.4 Effective Times Thickening vs. A/S and Thickening Parameter. Figures 17 to 20 show effective times thickening vs. A/S for the four conditions of polymer and/or chemical addition, and Table 26 summarizes the statistical comparison of the slope of these graphs with the TP. The variation of TP during the experiments is plotted in Figure 16. Although the TP variation is relatively large, it is not as large as that of A/S; this may be seen by comparing their coefficients of variation.

The case of polymer addition alone is clearly the most preferable. The value of the mean TP is the highest. The hypothesis that the TP is equal to the slope of the effective times thickening vs. A/S graph is confidently accepted at the five percent level of significance, and the probability plot indicates consistently higher TP values for all probabilities compared with the other three experimental conditions.

The present analysis is the only one which considers performance in terms of thickening and float concentration; the previous two considered effluent quality only. In the present case, addition of $FeCl_3$ is more clearly detrimental, and this is especially evident when considering the slope and TP values, since the higher TP the more efficient the performance. It also appears to be the case that with more efficient and more stable performance, the value of the TP more closely approximates the slopes, and the value of the intercept is closer to zero (when intercept = zero, slope = TP).

6.4.5 COD Reduction. Throughout this study, DAF performance was measured in terms of solids removal or sludge thickening, and phosphorus removal was also monitored. In addition, in phase 2, where DAF was being considered as a method for primary treatment, COD was also measured in most of the tests. The results are presented in Table 27. This table gives mean values only, and is thus only a cursory summary. No attempt was made to relate other performance parameters to COD removal.

The best performance in terms of COD removal was achieved when only polymer was added. This was expected, because total COD removal is associated with SS removal.

The reduction of soluble BOD through the plant was measured in five cases. Results were erratic (0-40 percent) and no conclusion is suggested.

6.4.6 Expected Performance. The results given in Table 28 are the values expected under the given operating conditions. The loading conditions were conservatively selected

TABLE 26 SUMMARY OF FLOAT TS AND A/S, AND STATISTICAL COMPARISON OF TP AND SLOPE. DAF PILOT PLANT PHASE 2

Chemical (mean dose)	Number of Samples	Float % TS Mean (σ)	A/S Mean (σ)	Plot LR/Slope/ Y	TP Mean (σ)	Null Hypothesis @ 5% and comments
None	20	5.85 (1.69)	0.347 (0.260)	0.86 2129 103	2684 (753)	Rejected (TP ≠ Slope)
Polymer 2.2 mg/g	21	5.66 (1.68)	0.166 (0.0776)	0.83 2756 57	3130 (856)	Accepted (TP = Slope)
$FeCl_3$ 31 mg/L	14	4.02 (2.0)	0.379 (0.490)	0.85 789 281	2261 (144°)	Irrelevant (Very wide data scatter)
Polymer 3.8 mg/g $FeCl_3$ 41 mg/L	10	4.94 (1.06)	0.205 (0.098)	0.73 1936 154	2571 (923)	Accepted (Too few samples for a definite conclusion)

A/S = Air to solids ratio
Plot = Graph of Effective Times Thickening vs. A/S
TP = Thickening Parameter
σ = Standard deviation
LR = Linear Regression Coefficient
Y = Intercept on Y axis

TABLE 27 SUMMARY OF COD REDUCTION. DAT PILOT PLANT PHASE 2

Condition	Number of Samples	Mean Influent COD (mg/L)	Mean Effluent COD (mg/L)	Mean COD Reduction (%)
No additions	16	515	316	39
Polymer Addition	19	492	271	45
$FeCl_3$ addition	11	356	273	23
Polymer and $FeCl_3$ addition	4	410	295	28

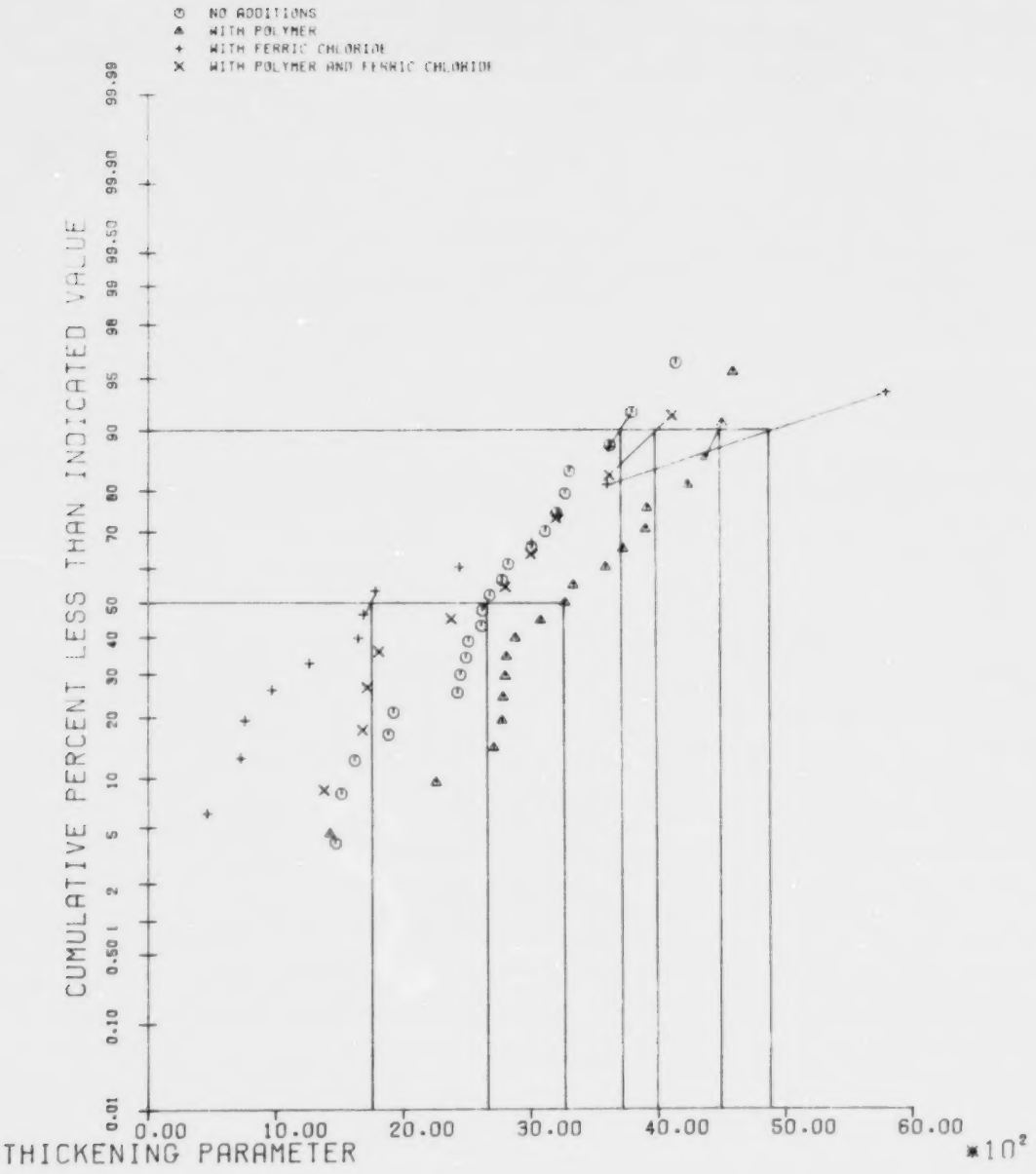

FIGURE 16 PROBABILITY PLOT FOR VARIATION OF THICKENING PARAMETER. DAF PILOT PLANT. PHASE 2

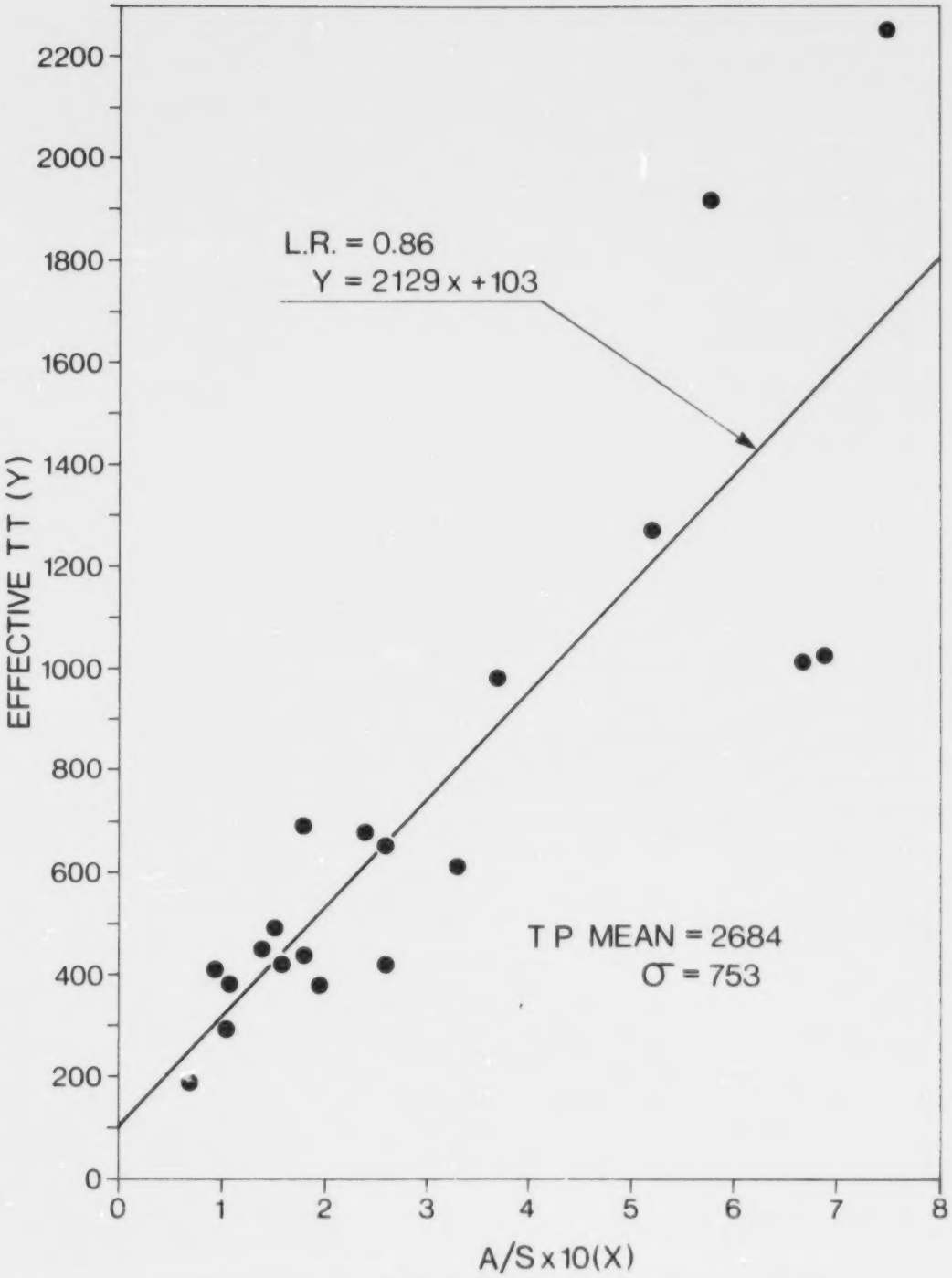

FIGURE 17 EFFECTIVE TIMES THICKENING vs. A/S, NO ADDITIONS. DAF PILOT PLANT. PHASE 2

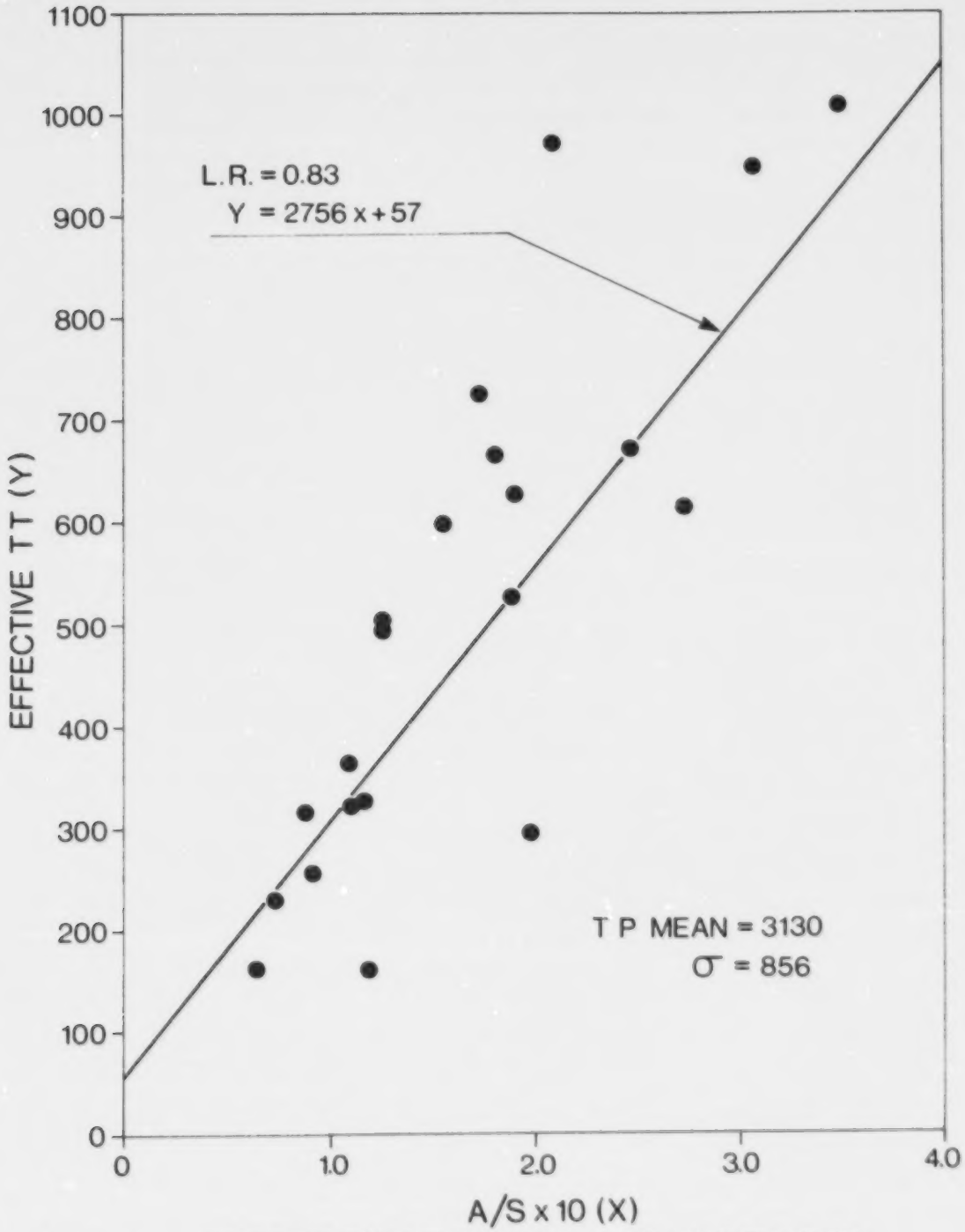

FIGURE 18 EFFECTIVE TIMES THICKENING vs. A/S, WITH POLYMER. DAF PILOT PLANT. PHASE 2

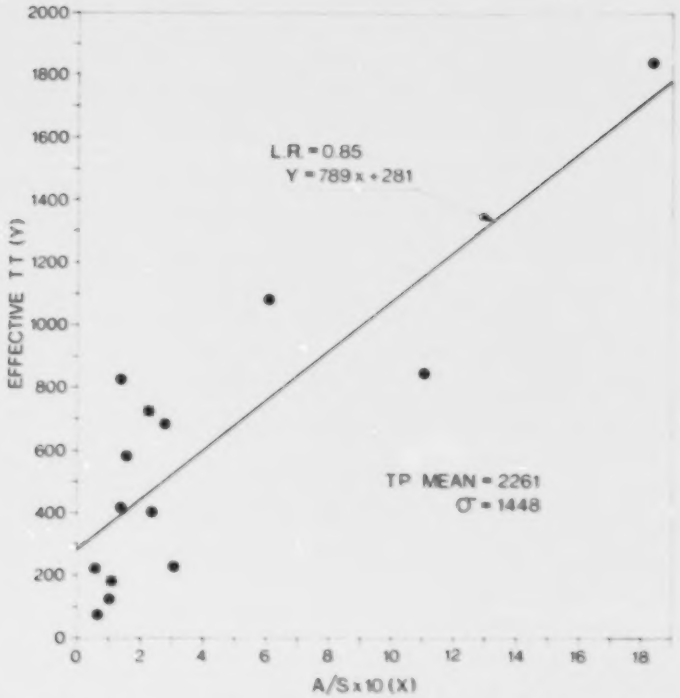

FIGURE 19 EFFECTIVE TIMES THICKENING vs. A/S, WITH $FeCl_3$. DAF PILOT PLANT PHASE 2

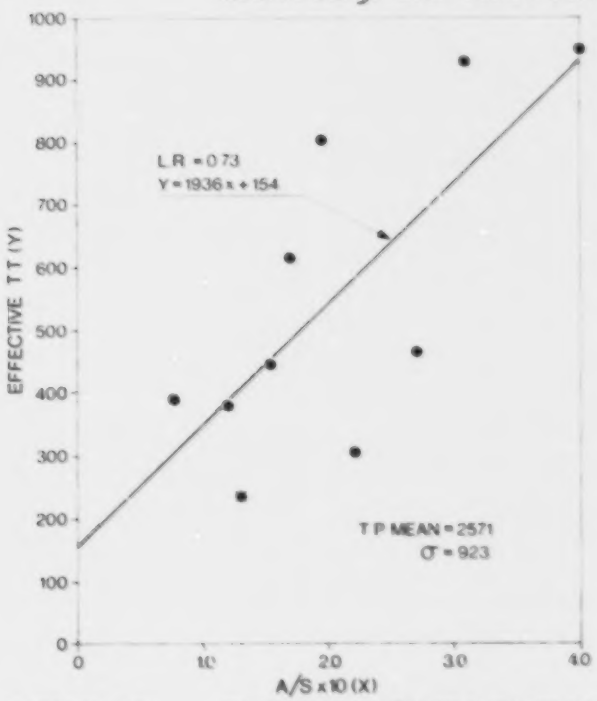

FIGURE 20 EFFECTIVE TIMES THICKENING vs. A/S, WITH POLYMER AND $FeCl_3$. DAF PILOT PLANT PHASE 2

TABLE 28 SUMMARY OF RECOMMENDED OPERATING CONDITIONS AND EXPECTED PERFORMANCE RESULTS. DAF PILOT PLANT PHASE 2

Recommended Operating Conditions	
Inflow	91 L/min
Influent SS	220 mg/L
Polymer	2.2 mg/g
$FeCl_3$	Not added
A/S ratio	0.3
Hydraulic Load	6.5 m/h
Solids Load	1.44 $kg/m^2 \cdot h$
Expected Results	
Effluent SS	40 mg/L
Float TS	5.7%
TP	3000

because the characteristics of raw sewage are always extremely variable. The DAF pilot plant operated successfully at hydraulic loadings up to 50 percent higher than shown and at zero polymer dose. Effluent SS as low as 18 mg/L and float TS up to 9.1 percent were obtained. The critical factor, as far as stable performance and effluent quality is concerned, is the air to solids ratio. It is vital that this be maintained at 0.3 or above. Flotation of raw sewage was far more sensitive to the A/S ratio than mixed liquor.

6.5 Scale-Up

The performances of the batch and pilot units are compared in Table 29. Since float samples from the batch flotation unit could not be obtained for analysis, the comparison is based only on effluent SS. Naturally, this limits the usefulness of the batch tests, especially where optimum performance in terms of thickening is not coincident with optimum clarification.

The batch unit gave a reliable indication of the A/S needed to obtain a stable effluent, with SS less than (say) 50 mg/L. The form of the effluent SS vs. A/S data was clearly unstable-stable, and the expected effluent SS at A/S greater than 0.2, when polymer and/or $FeCl_3$ were used, were similar in the batch unit and the pilot plant. Results from the batch unit with polymer alone showed no real improvement over no addition, but when $FeCl_3$ was also added, performance improved. These results were

TABLE 29 COMPARISON BETWEEN BATCH AND PILOT PLANT DAF PERFORMANCE. PHASE 2

		Batch	Pilot
Pressure (kPa)		276	360 - 415
A/S	No additions	0.3	0.4
	Polymer	-	0.3
	$FeCl_3$	-	0.3
	Polymer + $FeCL_3$	-	0.3
		Effluent SS vs A/S shows unstable-stable form.	Effluent SS vs A/S shows unstable-stable form.
Polymer dose		Effluent quality did not show clear improvement with polymer addition.	2.2 mg/g polymer addition improved all aspects of performance.
Float TS		Could not measure float solids.	See Table 26
Effluent SS (mg/L)	No additions	<65	<50
	Polymer	mean <50 for inf SS 250 mg/L	<40
	$FeCl_3$	<30 for $FeCl_3$ 10-25 mg/L	<50
	Polymer + $FeCl_3$	<40 for inf SS 200 mg/L	<20 (one test only)
		All for A/S $\geq$0.2	All for A/S $\geq$0.3
Slope		No measurements of float TS.	See Table 26
TP		No measurements of float TS.	See Table 26
Effect of $FeCl_3$ addition		Beneficial @ 15 mg/L to effluent quality when influent SS approx. 200 mg/L. Optimum performance with polymer + $FeCl_3$.	Beneficial to effluent quality only in conjunction with polymer. Detrimental to float.

confirmed by the pilot tests; however, the pilot tests did show that stability under abnormally high loads would be improved by polymer addition, and that slightly lower A/S values would be required to yield stable performance when polymer was being used. Batch tests cannot, by definition, give any information about stability under continuous operation.

The problem of deciding whether optimum conditions for clarification or for thickening should apply is exemplified by the results obtained from the pilot plant. The experiments showed clearly that $FeCl_3$ addition would be detrimental to thickening (i.e., would reduce the TP value), whereas effluent quality would be enhanced when $FeCl_3$ was added. These conflicting performance criteria could not be predicted from the batch tests, because float TS could not be measured.

6.6 Economics of Flotation of Raw Sewage

Flotation of raw sewage (SS 220 mg/L) produced a 5.7 percent float and removed 80 percent and 45 percent of the SS and COD, respectively. Primary sedimentation could with chemical addition produce similar results. The two alternatives can therefore be compared directly.

Design criteria for the flotation of raw sewage (where the hydraulic loading governed) were taken from phase 2 results. Overflow rates for sizing sedimentation units are in accordance with the current practice of the Ontario Ministry of the Environment. All design criteria that influence costs are included in Appendix K. Those pertinent to the flotation or settling of raw sewage are:

Operation	Average Hydraulic Loading	Peak Loading Factor
Flotation (Raw Sewage)	6.5 m/h	1.5
Primary Settling	0.82 m/h	2.5 - 3

Costs for the flotation or settling of raw sewage for flows of 4500, 45 500 and 227 000 m^3/d are based on recent construction contracts and annual charges applicable to southern Ontario. Details are included in Appendix K and totals pertaining to raw sewage are summarized in Table 30.

TABLE 30 COMPARATIVE COSTS: RAW SEWAGE

	Flow Rate		
	4500 m^3/d	45 500 m^3/d	22 700 m^3/d
Capital Costs			
Flotation (Raw Sewage)	$390 000	2 437 000	9 330 000
Primary Settling	125 000	965 000	4 260 000
Operation & Maintenance			
Flotation (Raw Sewage)	25 900	207 000	1 031 000
Primary Settling	7 100	45 700	212 600

7 EXPERIMENTAL RESULTS AND DISCUSSION - PHASE 3 (CONVENTIONAL ACTIVATED SLUDGE)

7.1 Jar Tests

The following chemical doses were the minimum required to give an effluent containing less than 0.1 mg/L soluble P reduced from 0.8 mg/L:

Alum	120 mg/L
$FeCl_3$	25 mg/L

This is consistent with the trend shown in phases 1 and 2, i.e., a considerably smaller quantity of $FeCl_3$, than alum is required to effect the same phosphorus removal. Lime was not investigated in this phase because of the poor results obtained in the two earlier studies. A complete tabulation of the jar test results is provided in Appendix D.

On the basis of the jar tests, ferric chloride at a dose of 25 mg/L was used in the pilot plant to study the impact on DAF performance on the addition of phosphorus removal chemicals.

7.2 Batch Flotation Tests

7.2.1 Determination of Optimum A/S. Mixed liquor from a conventional activated sludge plant was used as feed, and effluent from the plant was used as recycle. Six tests were performed to determine the optimum A/S. The parameters considered were float TS, effluent SS, and thickening parameter. The results are plotted on Figures 21 and 22.

With the mixed liquor, it was possible to obtain a distinct optimum point for A/S in terms of float TS; the highest concentration of 6.94 percent was obtained at an A/S of 0.028. At both lower and higher A/S values the float concentration dropped (Figure 29).

This clear-cut result for optimum A/S was not anticipated, but may be explained by the fact that the influent SS was relatively consistent over the entire set of six tests. In terms of effluent quality, however, there was no distinct relationship between effluent SS and A/S, contrary to phase 2 (raw sewage flotation) but consistent with previous work with mixed liquor and waste activated sludge (Gehr and Henry, 1976).

Figure 22 is a plot of effective times thickening vs. A/S; linear correlation is extremely good (0.989), but the slope (835) is significantly different from the thickening parameter (mean 1813) even at the one percent level, and the TP itself has a relatively large variation (coefficient of variation 0.32). In this case, therefore, the TP is not a suitable measure of performance, and a graph of effective times thickening vs. A/S is

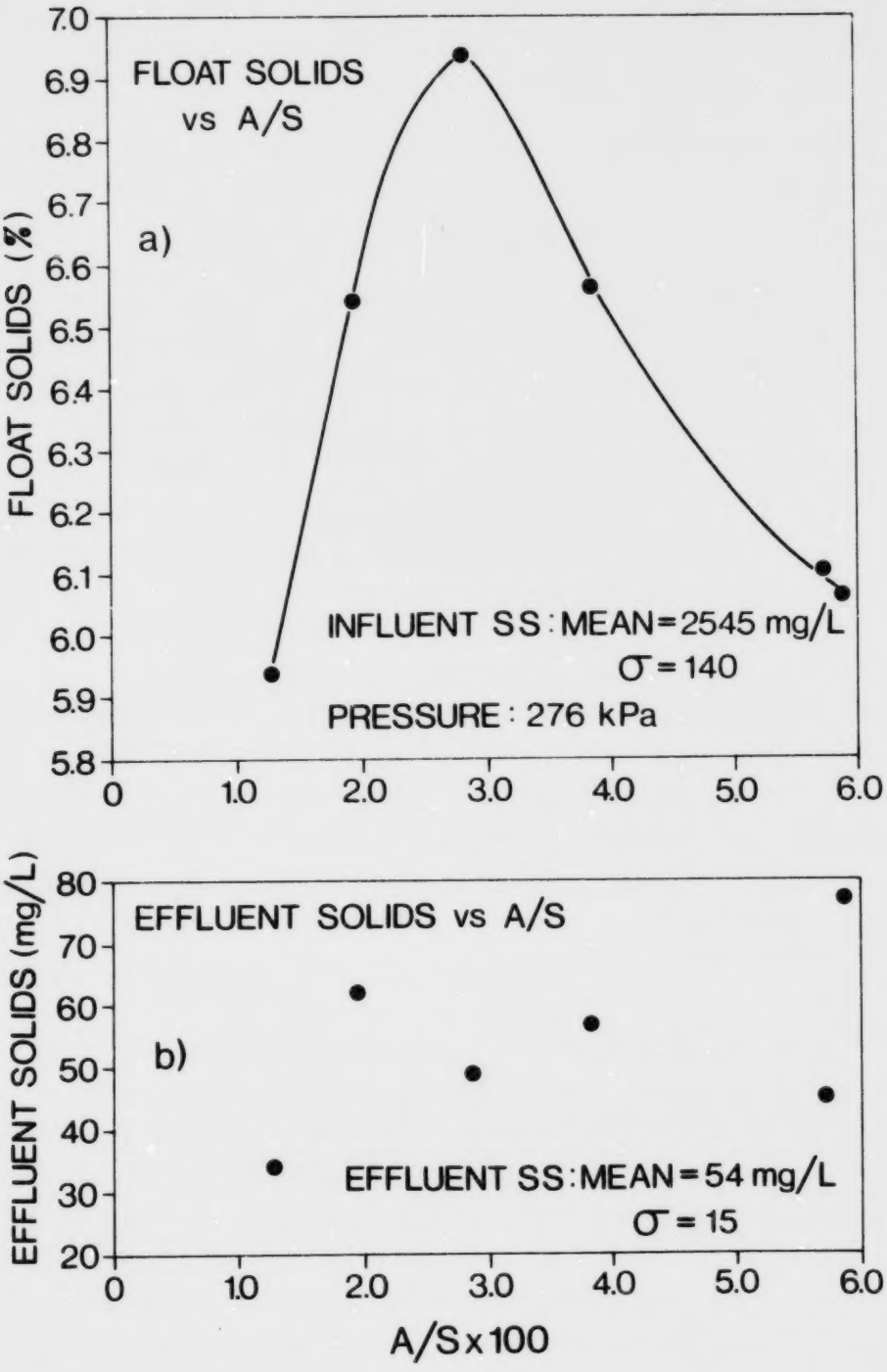

FIGURE 21 FLOAT AND EFFLUENT SOLIDS vs. A/S, NO POLYMER. PHASE 3

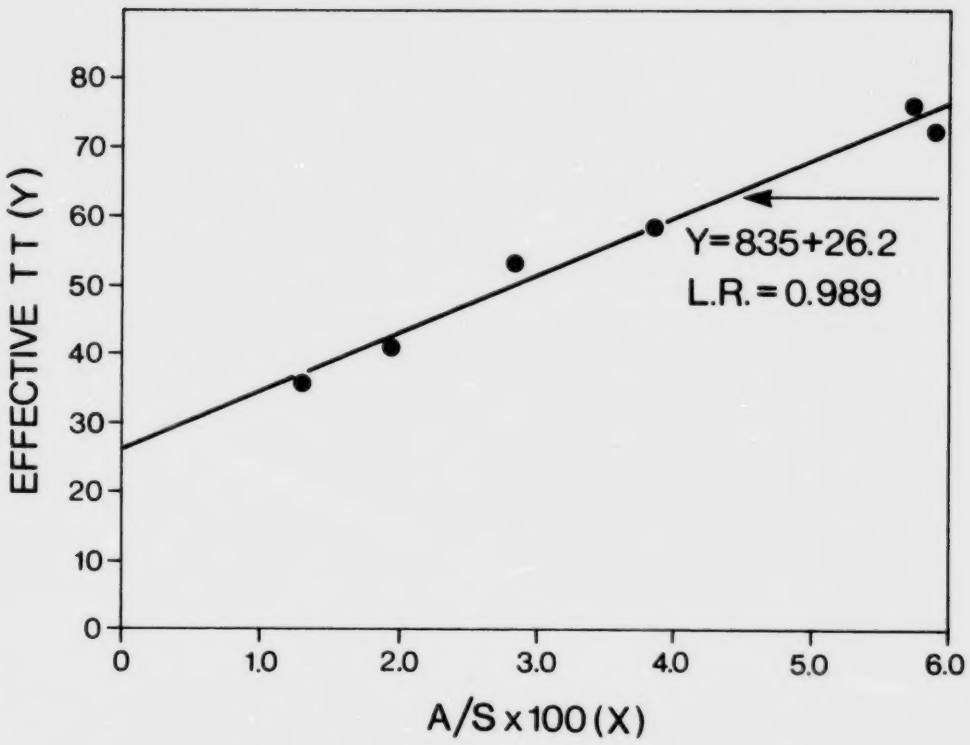

FIGURE 22 EFFECTIVE TIMES THICKENING vs. A/S, NO POLYMER. DAF BATCH FLOTATION UNIT. PHASE 3

necessary for design or prediction purposes. Alternatively, a thickening equation, which takes into account the fact that the line does not pass through zero, could be used to characterize performance.

7.2.2 Selection of Polymer. Twelve polymers were tested on an equal-cost basis. Percol 728 and Hercofloc 849, when considering both thickening and clarification, gave the best performance. Subsequent tests on Percol 728 and Hercofloc 849 showed that Percol 728 gave the thicker float over the entire range of doses tested, and generally a better effluent.

7.2.3 Determination of Optimum Polymer Dose. The results of the six tests done to determine optimum polymer dose are presented in Table 31. Effluent SS concentrations were virtually constant at lower polymer doses, but at the highest dose, 1.73 mg/g, an increase in effluent SS was evident. Highest float solids concentration was obtained at a polymer dose of 1.38 mg/g, and this value was chosen as one of the levels in the factorial design for the phase 3 pilot plant tests.

TABLE 31 DETERMINATION OF OPTIMUM POLYMER DOSE (PERCOL 728), BATCH TESTS. PHASE 3

Test	Polymer Dose (mg/g)	Influent SS (mg/L)	A/S x 100	Float TS (%)	TP	Effluent SS (mg/L)	Solids Capture* (%)	Solids Reduction** (%)
1	0	2645	2.79	6.68	1905	79	94	97
2	0.84	2645	2.82	6.49	1833	88	93	97
3	1.30	2560	2.89	6.32	1799	79	94	97
4	1.30	2560	2.78	6.68	1978	83	93	97
5	1.38	3203	2.19	7.21	2165	81	95	97
6	1.73	3203	2.21	7.01	2086	113	93	96

Note:

$$*\text{Solids Capture} = \frac{\text{Total (Inf. + Recycle) - Eff. SS}}{\text{Total SS (Inf. + Recycle)}} \times 100$$

$$**\text{Solids Reduction} = \frac{\text{Influent SS - Eff. SS}}{\text{Influent SS}} \times 100$$

Tests 3 and 4 were run, as far as possible, under similar conditions in order to determine the magnitude of the experimental error. Effluent SS concentrations were equal within the accuracy of solids determination methods, and float TS results differed by five percent. For this set of tests, with various polymer dosages, the overall range of float TS results was only 12 percent; hence, dosing with polymer did not really cause any appreciable improvement in performance. These results are contrary to those of previous studies (Gehr and Henry, 1976) and of phase 1 where, although float TS concentrations were unaffected, effluent SS concentrations were drastically improved.

The above contradictory results notwithstanding, the polymer chosen was the best out of the original range of 12. Batch flotation tests generally yield an effluent inferior to pilot tests. Furthermore, batch tests do not indicate whether improved stability is being achieved.

7.2.4 Effect of $FeCl_3$ Addition. The effects of the addition of $FeCl_3$ on DAF performance and soluble phosphorus removal are shown in Table 32. A drastic reduction in effluent SS was evident when $FeCl_3$ and polymer were used together. Optimum performance, both in terms of float TS and effluent SS, was obtained at a polymer dose of 1.9 mg/g and $FeCl_3$ dose of 25 mg/L. In this instance, the effluent was considerably better than that without any polymer or chemical addition.

7.3 Pilot Plant Operation

The major problem encountered during the pilot plant tests was with float removal. This problem did not occur during the previous phases for two reasons: in general, the float in this third phase was believed to be deeper than in phase 1 and was certainly deeper than in phase 2; secondly, continuous operation was sustained over a longer period in this phase than in phase 1.

The continuous flight skimmer was positioned in such a way that the blades did not sweep at the extreme end of the tank (effluent end). The designers probably assumed that the float would be removed from this area by natural displacement and a suction action. These processes did occur during the previous two phases. However, float tended to accumulate here in phase 3, and if not removed manually, would cause a deterioration in the effluent quality. Furthermore, since float depth was considerably greater than could conveniently be removed by hand scoop, the effective surface area available for flotation was reduced by about 12 percent. Theoretically, this reduction should have been reflected in the area loading calculations, but this was not done, mainly because the

TABLE 32 EFFECT OF $FeCl_3$ ADDITION. DAF BATCH FLOTATION UNIT, PHASE 3

Test	Polymer Dose (mg/g)	$FeCl_3$ Dose (mg/L)	Influent SS (mg/L)	Influent Sol P (mg/L)	A/S x 100	Float TS (%)	TP	Effluent SS (mg/L)	Effluent Sol P (mg/L)	Solids Capture (%)	Solids Reduction (%)	Soluble P Reduction (%)
1	0	0	2341	0.3	3.23	6.40	1783	67	0.3	94.0	97.1	0
2	0	25	2341	0.3	3.25	6.50	1798	40	0.2	96.5	98.3	33
3	1.9	25	2321	0.4	3.28	6.85	1895	26	0.3	97.6	98.9	25
4	1.9	15	2321	0.4	3.27	6.44	1786	34	0.3	96.9	98.5	25
5	1.7	35	2556	0.6	3.09	6.38	1700	32	0.1	97.4	98.7	88
6	1.7	45	2556	0.6	3.14	6.60	1731	39	0.1	96.8	98.5	88

actual area reduction was imprecise. The net effect would be that actual hydraulic and solids loadings would be higher than those calculated.

The solution to this problem would be to install a vertical or inclined baffle, whichever is convenient, to effectively shorten the tank, and enable the entire surface area to be skimmed. In the interests of consistency, no modification was done while tests for phase 3 were in progress.

7.4 Pilot Plant Results

The results of the pilot plant experiments in phase 3 were analyzed both statistically using analysis of variance of the results from the fractional factorial design only, and by the traditional method of graph plotting and considering the shape of the curves. All relevant experimental data, i.e., from the factorial set of experiments as well as from experiments carried out under different conditions, could be included in the second method of analysis.

7.4.1 Analysis of the Fractional Factorial Set of Experiments. It is generally assumed when conducting experiments that the independent variables will have "fixed" values for the duration of any repeated set of tests, and that each value will in fact be equal to the level chosen beforehand. In this study, mixed liquor from an activated sludge plant was used, and the MLSS naturally varied. The range was 2116 to 3130 mg/L, with a mean of 2830 and a standard deviation of 266 mg/L. No matter how well the operation of the DAF pilot plant was controlled, all parameters based on influent SS deviated from their chosen values. In the experimental design used, polymer dose (mg/g) and A/S were two such parameters, and the variation of these "independent" variables can be seen in Table 45. Furthermore, at the upper values of inflow and A/S, the limitations of the pressurizing plus recycle system precluded attainment of the chosen upper A/S value, and the actual measured A/S level was very close to the lower value. These variations of the two independent variables, A/S and polymer dose, could not be accounted for in the statistical analysis, and the confidence with which the statements of statistical significance are made is thus reduced.

The design of these experiments was a 1/2 replicate of 2^4, i.e., 2^{4-1}:

	Levels	
Independent Variables	Lower	Upper
chemical dose (mg/L)	0	25
influent flow (L/min)	45	68

polymer dose (mg/g)	0.88	1.39
A/S ratio	0.028	0.041

Dependent Variables

float TS (%)

effluent SS (mg/L)

thickening parameter

Treatments were repeated three times in eight sets involving 24 experiments. For further details see Appendix H.

A detailed analysis of the fractional factorial design is given in Appendix I. Table 33 provides the main effects and significant interactions.

TABLE 33 SIGNIFICANT EFFECTS AND INTERACTIONS, DAF PILOT PLANT. PHASE 3

	Float TS (%)		Effluent SS (mg/L)		TP	
	Low Polymer	High Polymer	Low Polymer	High Polymer	Low A/S	High A/S
No chemical	6.64	6.79	65	28		
With $FeCl_3$	6.13	7.53	36	18		
Low Flow					1674	1901
High Flow					2039	2528

Low Polymer = 0.88 mg/g; High polymer = 1.39 mg/g
Low A/S = 0.028; High A/S = 0.041
$FeCl_3$ dose = 25 mg/L
Low Flow = 45 L/min; High flow = 68 L/min

These effects and interactions may be summarized as follows:

a) Polymer and chemical interact to produce the most concentrated float. However, the presence of $FeCl_3$ at a low polymer dose has a deleterious effect on the float concentration. A high polymer dose will improve the float slightly, but drastic improvement is evident only when $FeCl_3$ is present.

b) Polymer and chemical act independently to improve the effluent quality. Chemical addition alone will cause a reduction in effluent SS regardless of the polymer dose,

nd a high polymer dose improves the effluent regardless of whether chemical is present or not. When chemical and a high polymer dose are added, the effluent SS i further reduced.

c) A/S and flow rate affect the TP independently. The TP is increased by a higher A/S and by a higher flow, and the highest TP is obtained at the upper value of these parameters.

The analysis of the fractional factorial set of experiments yielded interesting results, some unexpected. However, the variances of the independent variables were not taken into account. A/S was reasonably consistent at the lower flow rate but tended to deviate more from the chosen value as the recycle rate increased.

The interaction of chemical and polymer on float solids concentration was the most interesting result to emerge from the analysis. $FeCl_3$ and polymer interact to produce the best float, but sufficient polymer must be present to derive maximum benefit from the chemical addition. The basis for this interaction is not clear, neither is it clear why the presence of chemical with insufficient polymer is harmful to the float concentration. The explanation must lie with the mechanism(s) of flocculation (physical, electrical, chemical, or a combination of these) but with the data available it is not possible to expand on this suggestion.

The effect of chemical and polymer addition on effluent solids was as expected, and the statistical analysis showed that each factor is independent of the effect of the other, i.e., there was no interaction. It is possible that the coagulation mechanisms of each are different, and that particles affected by the chemical will not be those affected by the polymer. Credence is added to this theory when the results of this analysis are compared with the graphical analysis (section 7.4.3).

The rise in TP with increasing A/S is contrary to results from previous studies (Gehr and Henry, 1976), but is not inconsistent with results of this study (see sections 6.4.4, 7.2.1, and 7.4.3).

TP rose with increasing flow, i.e., thickening does not improve at higher flows. The reason for this is thought to be that, since the float blanket depth could not be measured and, therefore, accurately controlled, a thicker float developed at the higher inflow rate (higher solids loading). Provided solids carry-over did not occur, the thicker float blanket would cause the float detention time to increase, and the upper layer of this blanket to be thicker. There would be an optimum float blanket depth above which no

improvement in thickening would occur, but this depth could not be measured, nor studied during this project.

The variation in float depth could considerably affect the interpretation of all the results and conclusions regarding thickening performance in this phase, as well as in phase 1. An important variable, float blanket thickness, has been ignored, and this could account for the many cases where regression was poor and considerable data scatter observed. Throughout all tests in each phase, however, the water level remained constant (increased flows have only a minor effect); thus, the variable overall float thickness will not have as great an effect as if the level of the float above the water level had changed drastically (see Bratby and Marais, 1975).

7.4.2 Analysis of Results by Graphical Means. Effective times thickening vs. A/S was plotted for five cases of polymer and chemical addition. Table 34 summarizes the linear regression analysis of these graphs, together with the relevant thickening parameter and the results of the statistical comparison. Cases I and III (Table 34) are shown graphically in Figures 23 and 24, respectively. Case III includes all tests in which chemical was added; hence, the wide range of polymer doses. This set of tests was grouped to assess whether chemical addition alone, regardless of polymer dose, would affect performance. The effect of variable polymer dose on thickening also could be determined.

Conclusions drawn from the thickening analysis were:

1) Apart from case II, for which no explanation is evident, acceptable linear correlation was obtained for all conditions, and it can be assumed that this method of data analysis is usable.
2) Neither polymer dose nor chemical addition had a clear effect on the slope and the intercept.
3) Case III shows only fair linear correlation, even though it includes the largest number of samples of all the five cases. It appears that the range of polymer doses has affected thickening performance.
4) The mean TP does rise by about five percent between tests at zero and 25 mg/L chemical addition. Cases I and IV (no chemical) and cases II and V (with chemical) illustrate this conclusion. The effect is more pronounced in the case of chemical addition.
5) In neither case is slope equal to TP according to the standard "t" statistical test at the five percent level of significance. It appears, therefore, that performance

TABLE 34 THICKENING ANALYSIS, EFFECTIVE TIMES THICKENING vs. A/S. DAF PILOT PLANT PHASE 3

Case	Replicates	Polymer Dose (mg/L)			$FeCl_3$ (mg/L)	Linear Regression			TP		TP = Slope @ 5% level ?
		Range	Mean	σ		Slope	Intercept	Coefft	Mean	σ	
I	10	0.80-1.0	0.88	0.07	0	1490	12.7	0.90	1991	313	No
II	7	0.80-1.0	0.93	0.07	25	440	51.9	0.21	1966	511	No
III	16	0.42-1.67	1.10	0.38	25	1630	10.1	0.70	1942	425	No
IV	8	1.35-1.60	1.46	0.05	0	1100	30.8	0.66	2067	463	No
V	5	1.35-1.60	1.46	0.12	25	1140	34.3	0.85	2081	347	No

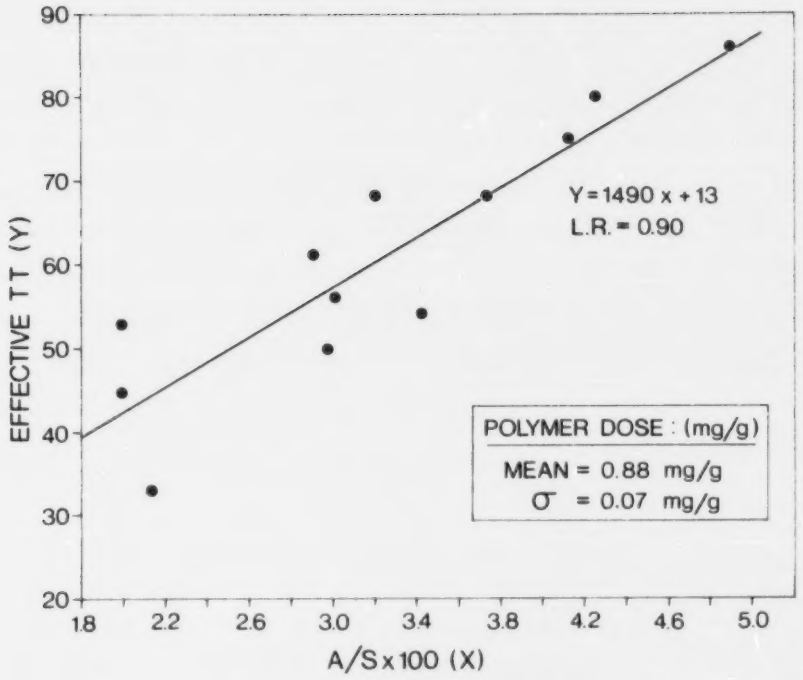

FIGURE 23 EFFECTIVE TIMES THICKENING vs. A/S, WITHOUT CHEMICAL. DAF PILOT PLANT PHASE 3

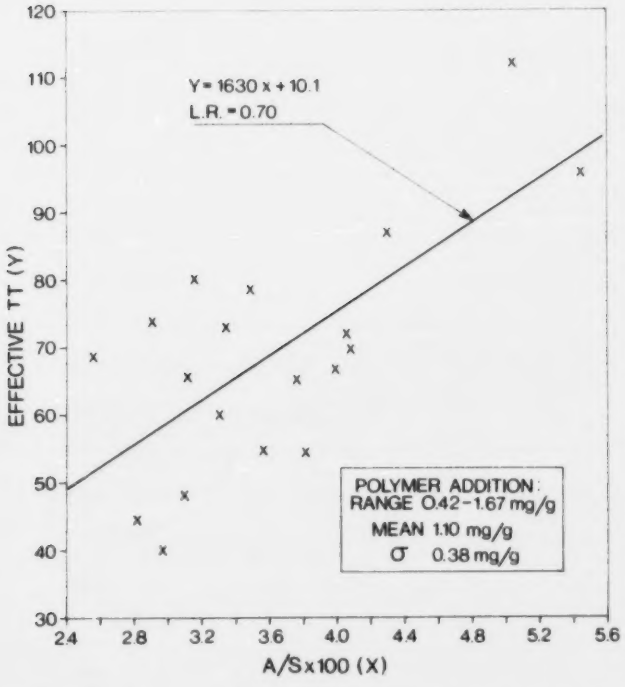

FIGURE 24 EFFECTIVE TIMES THICKENING vs. A/S, WITH CHEMICAL AND POLYMER. DAF PILOT PLANT PHASE 3

within any particular treatment condition is better characterized by a thickening equation than by a TP.

The meaning and application of mean thickening parameter (TP) and thickening equation require explanation. The mean TP is the average of all the TP's in a particular test series. The individual TP values vary considerably over any series, and over the range of A/S ratios (Table 34). The TP was developed originally by Gehr and Henry (1976) to a) eliminate influent SS from the number used to characterize performance, and b) have available a "useful" number to indicate DAF performance in terms of thickening only. It was found that polymer addition did not affect the float TS; hence, the TP would also be unaffected by polymer addition. It was also suggested that TP would be constant over any practical A/S range.

The results of phases 1 and 2 of this study showed that TP is not always constant when A/S is varied, and that in those cases a thickening equation of the line of effective times thickening vs. A/S is a better way of characterizing and predicting performance for a particular set of influent SS concentrations and air additions.

In phase 3, A/S varied within each set of tests, and since TP was not constant nor equal to the slope of the appropriate graph, TP would clearly not be a suitable design or performance parameter to account for the effects of varying A/S. However, the average TP could be considered an indicator of performance over this particular range of A/S ratios. Thus, if polymer addition had a significant effect on thickening, or if any other changes were to be made to the plant that would affect the float TS, this would be reflected in a change in the value of the average TP taken over a range of A/S ratios.

Performance from one test to another was not adequately represented by a single number, the TP. Another method, such as a thickening equation, should be considered. It can be concluded, however, that polymer addition in conjunction with chemical addition does improve thickening performance.

Float TS vs. A/S was plotted for the same five sets of conditions of chemical and polymer addition as in the thickening analysis. In general, the trend was towards a slightly higher float TS at higher A/S, but no linear correlation was evident, nor was it possible to distinguish performance differences between one set of conditions and another. It is assumed that, within the range of A/S values used, i.e., 0.0187 to 0.0545, there will be little or no change in float solids concentration.

The five sets of conditions were again used in plotting effluent SS vs. A/S. No trend was evident, and it can be concluded that A/S variation will not affect effluent quality.

Figure 25 shows the effect of polymer addition on float TS. It is evident that chemical is required before polymer addition significantly affects float solids concentration. Furthermore, when considering Figure 33b for any particular A/S, a more concentrated float may be expected at higher flows; the majority of points representing 68 L/min are above the regression line, whereas the majority of points for 45 L/min are below the line.

Graphs of effluent SS vs. polymer dose were plotted for a case with and without chemical (Figures 26 and 27). An optimum range of polymer doses was identified at which the lowest and most stable effluent SS concentrations were obtained. This range was the same on both graphs, and lay between 1.4 and 1.6 mg/g polymer dose. However, the effluent obtained with chemical addition was superior; an SS of 20 mg/L was possible without chemical, and 15 mg/L with. Influent flow did not affect effluent quality. The plant was clearly underloaded with this particular mixed liquor, even at the highest flow rate of 91 L/min.

7.4.3 Comparison of Statistical and Graphical Analyses. The following comparison of the two methods of analysis is subdivided into sections where the same conclusions were reached from both analyses, and others where conclusions were reached from only one analysis or the other.

a. Conclusions from both statistical and graphical analyses:

   i) A more concentrated float is produced at a higher polymer dose, and this trend is clearer when chemical is present.

   ii) Float concentration is unaffected by A/S (indistinct trend in graph; A/S insignificant in statistical analysis).

   iii) Effluent solids concentration is unaffected by A/S (as in ii).

   iv) Polymer and chemical addition independently improve the effluent.

   v) Mean TP rise when polymer and chemical are added is small.

   vi) Float is more concentrated at higher flows (most high-flow points are above the regression line in the float vs. polymer graph; TP higher at higher flow).

b. Conclusions from statistical analysis only:

   i) Polymer and chemical interact in their effect on float solids concentration.

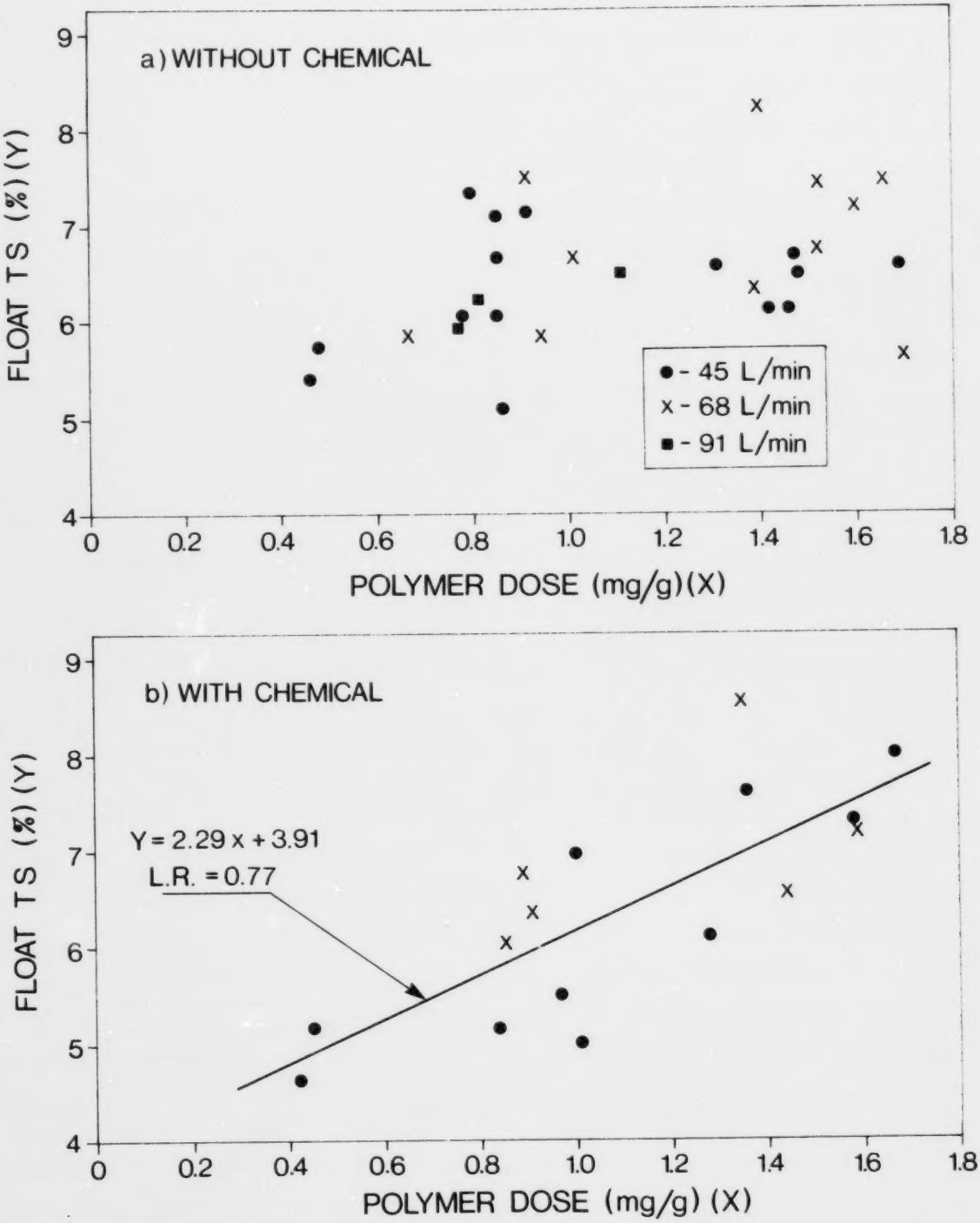
a) WITHOUT CHEMICAL
FLOAT T S (%) (Y)
POLYMER DOSE (mg/g)(X)
● - 45 L/min
x - 68 L/min
■ - 91 L/min
b) WITH CHEMICAL
Y = 2.29 x + 3.91
L.R. = 0.77
FLOAT T S (%) (Y)
POLYMER DOSE (mg/g) (X)

FIGURE 25 FLOAT SOLIDS vs. POLYMER DOSE FOR ALL A/S AND FLOWS. DAF PILOT PLANT. PHASE 3

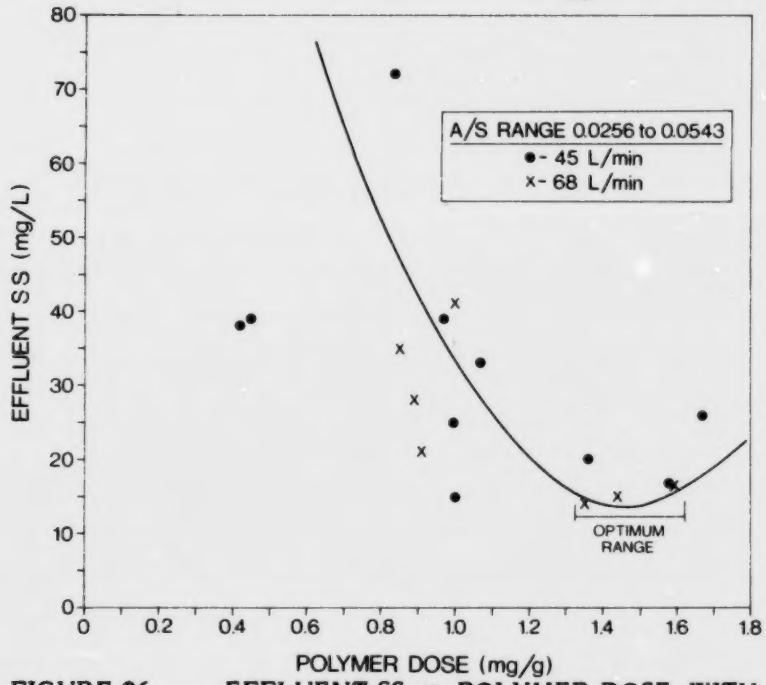

FIGURE 26 EFFLUENT SS vs. POLYMER DOSE, WITH CHEMICAL. DAF PILOT PLANT PHASE 3

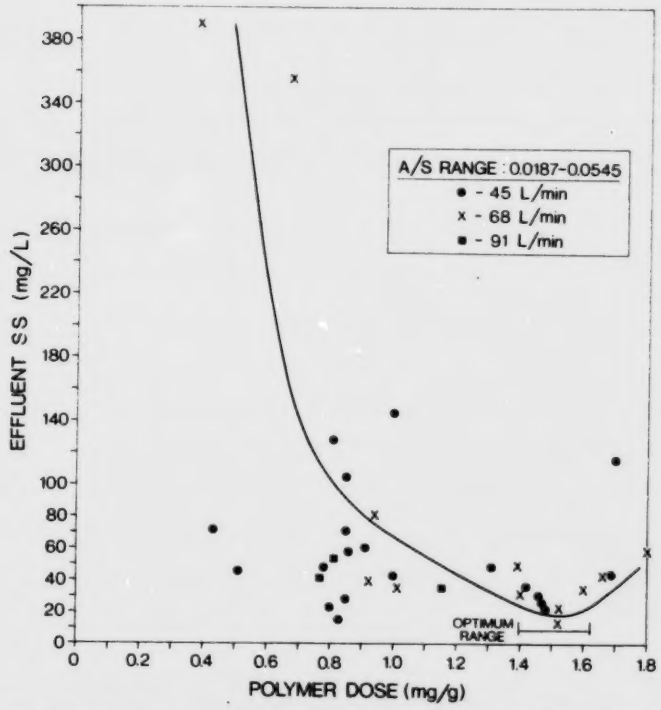

FIGURE 27 EFFLUENT SS vs. POLYMER DOSE. WITHOUT CHEMICAL, ALL A/S. DAF PILOT PLANT PHASE 3.

ii) The TP is independently affected by the flow rate and the A/S ratio.

c. Conclusions from graphical analysis only:

i) A thickening equation was more appropriate than the TP to describe thickening performance where A/S was the only variable.

ii) There was an optimum polymer dosage for achieving low effluent SS beyond which effluent SS would rise again. The fact that the presence of chemical caused an improvement in the effluent SS, although the optimum polymer dose remained the same, and addition of even more polymer again resulted in a rise in effluent SS, confirms that the polymer and chemical operate by different mechanisms, and/or that they are responsible for flocculating different (sized) particles.

7.4.4 Solids Balance. Solids balance measurements were taken as part of the experimental routine in most of tests 11 to 45. The results are presented in Appendix J. The overall mean error was only ± 1.6 percent, disregarding the two extreme upper and lower errors. Considering the nature of the materials handled and measured, these results are acceptable. Tests 17 and 26, which had solids balance errors above 15 percent, were omitted from the statistical analysis of the factorial experiments because three other tests under similar conditions in each case gave satisfactory results.

It may be observed from the skimmer operating data that an attempt was made to link float solids removal with solids load to maintain a constant float blanket depth. However, since the blanket depth could not be measured, these operating adjustments were, at best, educated guesses, and this may explain why in some instances the solids balance errors were relatively high; float removal was not keeping pace with, or was exceeding, the inflow of solids, and the float blanket thickness was undergoing a corresponding change.

7.4.5 Expected Performance. Table 35 summarizes recommended operating conditions and expected performance under the conditions given. The expected results are the optimum values obtained from the analysis of the fractional factorial design, and may be regarded as being optimistic. The operating conditions tabulated are applicable for the optimum values of the three performance parameters (i.e., lowest effluent SS, highest float TS, and highest TP). Cost was not considered in determining these conditions and results. Later cost calculations required a lower A/S (hence recycle ratio), and the results would not be as favourable.

TABLE 35 SUMMARY OF FLOTATION OF CONVENTIONAL ACTIVATED SLUDGE MIXED LIQUOR. DAF PILOT PLANT PHASE 3

Optimum Operating Conditions	
Inflow	68 L/min
Influent SS	2900 mg/L
Polymer	1.45 mg/g
$FeCl_3$	25 mg/L
Air Saturation	60%
A/S	0.041
Hydraulic Load	4.88 m/h
Solids Load	13.7 $kg/m^2 \cdot h$
Expected Results	
Effluent SS	18 mg/L
Float TS	7.5%
TP	2500

7.5 Scale-Up

The performances of the batch and continuous-flow units are compared in Table 36. In general, the comparison is excellent. In contrast with the previous two phases, considerably fewer batch tests than pilot tests were conducted. This could account, partially if not wholly, for the discrepancies in the optimum A/S values, lowest effluent SS, and effect of $FeCl_3$ addition.

Differences in optimum A/S values and lowest effluent SS were both approximately 30 percent. Only six tests were done to obtain the optimum A/S in the batch tests, and there were no replicates. Considering the variables involved and the accuracy of measurement, a 30 percent difference is not excessive. The superior effluent obtained in the pilot test is consistent with results from previous study (Gehr and Henry, 1976) and from the earlier phases. This is probably because of less turbulence and more efficient use of polymer in the continuous flow unit.

The effect of chemical addition on the float was not indicated clearly in the batch tests. Only five tests were done using $FeCl_3$, and these involved three different doses, and three different doses of polymer. The results did show that 25 mg/L of

TABLE 36 COMPARISON OF BATCH AND PILOT PLANT DAF PERFORMANCE. PHASE 3

	Batch	Pilot
Pressure (kPa)	276	283-380
Optimum Recycle Ratio	2.0	2.5
Optimum A/S	0.028	0.041 (s)
Optimum Polymer Dose (mg/g)	1.38	approximately 1.45 (g)
$FeCl_3$ Dose (mg/L)	25	25
Effect of $FeCl_3$ addition	1) Improved effluent when no polymer present 2) Further improvement of effluent with polymer addition 3) No detectable effect on float	1) Improved effluent independently of polymer concentration. 2) Polymer/chemical interaction effect on float
Optimum Float TS (%)	7.21	7.53 (s)
Optimum Effluent SS with polymer (mg/L)	26	18 (s)
Optimum TP	2165	2500 (s)

Note: s = results from statistical analysis
g = results from graphical analysis

chemical addition would give optimum thickening performance, but interaction effects with polymer could not be detected.

7.6 Economics of Flotation of Mixed Liquor from Activated Sludge

Flotation of mixed liquor (2800 mg/L) from a conventional activated sludge plant resulted in a 7 1/2 percent float. To realistically compare this process with sedimentation, which produces a 1 to 1 1/2 percent sludge, the waste activated sludge from settling must be further concentrated. As DAF has become an acceptable method for accomplishing this, the costs for flotation thickening have been added to the final settling tank costs.

Sizes of the units were determined from the hydraulic loadings except for flotation thickening, where solids loading applies. Complete design criteria are contained in Appendix K. Those used in this section are:

	Operation	Average Loading	Peak Loading Factor
1.	DAF (Mixed Liquor)	4.88 m/h*	1.3
2.	Sedimentation/Flotation		
	a) Final Settling	0.82 m/h**	2
	b) Flotation (waste activated sludge)	9.8 kg/m^2.h***	2

* from the phase 3 pilot data
** current practice Ontario Ministry of the Environment
*** manufacturers' recommendations

Capital costs for the flotation of mixed liquor and for the sedimentation alternative were estimated from recent construction contracts and manufacturers' equipment prices updated to October 1977. Power costs, labour rates and polymer prices are applicable to southern Ontario.

Total costs for units to handle flows of 4500, 45 500 and 227 000 m^3/d are shown in Table 37. Prices do not include feed or effluent pumps, land, or other charges.

TABLE 37 COMPARATIVE COSTS: ACTIVATED SLUDGE

	Flow Rate		
	4500 m^3/d	45 500 m^3/d	227 000 m^3/d
Capital Costs			
1. DAF (Mixed Liquor)	$390 000	2 978 000	11 000 000
2. Sedimentation/Flotation			
a) Final Settling	134 000	1 025 000	4 500 000
b) Flotation (Thickening)	121 000	422 000	676 000
	$255 000	1 447 000	5 176 000
Operation & Maintenance			
1. Flotation (Mixed Liquor)*	68 200	718 500	3 600 000
2. Sedimentation/Flotation			
a) Final Settling	5 100	20 300	104 000
b) Flotation** (Thickening)	4 800	19 100	58 200
	$ 9 900	39 400	162 200

* Includes polymer costs
** Includes polymer + $FeCl_3$ costs

8 PERFORMANCE AND COST COMPARISONS

8.1 Batch and Continuous-Flow DAF Units

The comparison between the batch and continuous flow units is limited to those parameters that are exclusive of time. These are effluent SS, float TS, and TP or TE, as well as the operating conditions of pressure, recycle ratio, A/S, and polymer/chemical dose. Solids and hydraulic loadings and the effects of area and depth cannot be compared. (The literature contains frequent references to the "Rise Rate" (Eckenfelder and Ford, 1970; Turner, 1975; Wood and Dick, 1973) as a method for introducing the time element into analyses from batch tests, but as a result of previous experience (Gehr and Henry, 1976), this factor was not used in this study.

Summaries of comparisons between batch and pilot plant performance are given in Tables 18, 29, and 36 for phases 1, 2 and 3, respectively. In each case conditions required to achieve optimum performance have been compared. The following points are noted:

a) The optimum effluent SS is always lower in the pilot plant.

b) The optimum A/S required for the pilot plant is between 0 and 40 percent higher than for the batch unit.

c) The improvement in effluent quality with polymer addition is not as apparent in the batch unit as in the pilot operation. Polymer addition improves stability under continuous operation, and this cannot be measured on a batch unit. The polymer used in the pilot plant was chosen on the basis of comparative tests in the batch unit. This selection was not confirmed in the pilot tests because of time limitations. The polymer requirements of the batch unit accurately reflected those of the pilot plant with the exception of phase 2 where polymer was useful in stabilizing effluent quality.

d) The pressure used in the pilot unit was always higher (up to 50 percent, depending on the recycle flow) than that used in the batch unit, because the latter had a maximum design pressure of 345 kPa. However, this difference was accounted for in the measurements of dissolved oxygen. The effects of varying air bubble sizes at different pressures is negligible in comparison with other experimental errors.

e) Whenever solids measurements could be taken (phases 1 and 3) float solids concentration between the batch and pilot units was comparable within approximately 10 percent.

f) The effects of $FeCl_3$ addition on flotation performance were first studied in batch tests. In phase 1 the batch and pilot units' performances compared poorly, possibly due to a limited amount of data. The effects of $FeCl_3$ addition in phases 2 and 3 were similar in kind, but the size of the response of the batch and pilot units was different in each case.

g) Where TP and/or slope were comparable, notably in phase 1, the differences between batch and pilot unit values were not greater than 12 percent.

In summary, the batch unit gave a good first approximation of the performance expected from the pilot plant under suitable loading conditions. Air requirements, polymer dose, and performance in terms of float and effluent solids concentrations could be predicted with reasonable accuracy. An example of the use of batch test data for process design is given in Appendix E.

8.2 Pilot Plant Performance

A summary of pilot plant performance is presented in Table 38. The following points are noted:

a) The recommendations of the manufacturer, Komline-Sanderson, are:
   - Hydraulic load no greater than 2.19 m/h
   - Solids load no greater than 9.0 $kg/m^2.h$

   The actual hydraulic (governing) loading exceeded these values in all cases. In fact with low influent SS, as for example in the raw sewage, the hydraulic load could be as much as triple that recommended. Limited experience with short runs suggests that the hydraulic loads could be increased by at least 50 percent above the recommended values without deterioration in DAF performance. The lower values used for sizing are intended to provide a margin of safety.

b) Air saturation was marginally lower in phase 2 (raw sewage), than in the other two phases, and did not even reach the relatively inefficient value of 60 percent.

c) Because raw sewage is difficult to flocculate, flotation required approximately 10 times more air, per unit mass, than did the liquors from extended aeration and conventional activated sludge. The poor flocculating capability is also reflected by the higher effluent solids concentration. However, raw sewage was the most amenable of the three suspensions to flotation thickening, as indicated by the thickening parameter.

TABLE 38 SUMMARY OF PILOT PLANT PERFORMANCE

	PHASE 1 (Extended Aeration)	PHASE 2 (Raw Sewage)	PHASE 3 (Conventional Activated Sludge)
Inflow (L/min)	32	91	68
Influent SS (mg/L)	4 600	220	2 900
Hydraulic Load (m/h)	2.27	6.50	4.88
Solids Load ($kg/m^2 \cdot h$)	10.4	1.44	13.7
Air Saturation (%)	60	52	60
A/S	0.028	0.30	0.026 (0.41)
Recycle Flow (L/min)	80	109	102 (170)
Recycle Ratio	2.5	1.2	1.5 (2.5)
Polymer dose (mg/g)	0.9	2.2	1.45
$FeCl_3$ dose (mg/L)	0-60	0	25
Effluent SS (mg/L)	< 15	40	18
Float TS (%)	3.8	5.7	6.5 (7.5)
TP	1 000	3 000	2 500

Note: Parameters above are suggested for design purposes. The values shown in brackets ( ) for phase 3 are the upper values determined statistically, but are considered uneconomical for design.

d) The high polymer dose indicated for raw sewage is that required for stable operation under varying influent solids concentrations. With a more uniform waste, polymer may not be required at all.

e) Although the float TS in phase 1 was considerably lower than that in the other two phases, it is probable that this concentration could have been increased by other combinations of ferric chloride and polymer dosage. Time constraints precluded further experiments.

8.3 Comparison of Costs

Flotation as an alternative to sedimentation for the separation of solids in mixed liquor or raw sewage cannot be justified in municipal waste treatment on economic grounds. This is evident from the tabulation in Table 39.

TABLE 39 COMPARISON OF COSTS: FLOTATION vs. SEDIMENTATION

Treatment		Capital and Operating Costs (x $1000)					
		4500 m^3/d		45 500 m^3/d		227 000 m^3/d	
		CAP	OP	CAP	OP	CAP	OP
1)	Extended Aeration ML Flotation	670	70	5 484	587	22 680	3 310
	Final Settling + Flotation Thickening	293	11	1 735	47	6 428	177
2)	Flotation of Raw Sewage	390	26	2 437	207	9 330	1 031
	Primary Settling	125	7	965	46	4 260	213
3)	Activated Sludge ML Flotation	390	68	2 978	719	11 000	3 600
	Final Settling + Flotation Thickening	255	10	1 447	39	5 176	162

Table 39 shows that using flotation as an alternative to sedimentation increases capital costs 1 1/2 to four times and operating costs five to 20 times, depending upon the application and size of plant.

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BIBLIOGRAPHY

Albert, J.T., "Waste Activated Sludge Thickening by Countercurrent Flotation", paper presented at the 32nd Annual Purdue Industrial Waste Conference, Lafayette, Indiana, May 1977

Ashman, P.S., "Operational Experiences of Activated Sludge Thickening by Dissolved Air Flotation at the Aycliffe Sewage Treatment Works", paper presented at the Flotation for Water and Waste Treatment Conference, Water Research Centre, Felixstowe, England, June 1976.

Barrett, F., "Electroflotation - Development and Application", Water Pollution Control 74(1): 59-62, 1975. (British)

Baum, R.A., and Hurst, G.E., "Treatment of Municipal and Industrial Wastes by Flotation", Proc. 8th Ind. Waste Conf., Purdue Univ. p. 10, 1953.

Bratby, J. and Marais, G.V.R., "Saturator Performance in Dissolved-Air (Pressure) Flotation", Water Research 9 (11): 929-936, 1975.

Bridle, T.R., et al., "Start-Up of a Full-Scale Nitrification/Denitrification Treatment Plant for Industrial Waste". Proc. 31st Annual Purdue Industrial Waste Conference, p. 807, May, 1976.

Brown, B.R., et al., "Experiments on the Dewatering of Digested and Activated Sludge," Wat. Poll. Control 71(1): 61-84, 1972. (British).

Burfitt, M.L., "The Performance of Full-Scale Sludge Flotation Plant", Wat. Pollut. Control 71(4): 474, 1975. (British).

Campbell, H.W., and Le Clair, B.P., "Effects of Control Variables and Sludge Characteristics on the Performance of Dewatering and Thickening Devices", paper presented at the Sludge Handling and Disposal Seminar, Toronto, Ontario, September, 1974. Canada-Ontario Agreement on Great Lakes Water Quality, Conference Proceedings No. 2.

Campbell, H.W., et al., "Some Aspects of Chemical Sludge Thickening and Dewatering", paper presented at the Alternatives for Nutrient Control Seminar, Environment Canada, Kelowna, B.C., October, 1975.

Campbell, H.W., et al., "Sludge Dewatering Design Manual", Canada-Ontario Agreement on Great Lakes Water Quality Project No. 75-3-22, Research Report No. 72, Ottawa, 1978.

Chambers, D.B., and Cottrell, W.R.T., "Flotation: Two Fresh Ways to Treat Effluents", Chemical Engineering, 83(16):95, August 2, 1976.

Chase, E.S., "Flotation Treatment of Sewage and Industrial Wastes", Sew. and Ind. Wastes 30(6):783, 1958.

Climenhage, D.C. and Stelzig, A., "Biological Process for Nitrogen - B.O.D. Removal at Maitland Works, Dupont of Canada, Ltd.", Proc. 20th Ont. Ind. Waste Conf., Ontario Ministry of the Environment, Toronto, June, 1973.

Collins, R., and Burns, C., "Full Scale Operating Tests Prove Sewage Plant Operates as Designed", Eng. News Record 146(16):42, April 19, 1951.

Davies, O.L. (ed.), The Design and Analysis of Industrial Experiments, 2nd Ed., Hafner Pub. Co., N.Y., 1956.

Davis, C., Johannesburg City Engineer's Department. Personal communication. July, 1977. (South Africa).

Dick, R.I., "Sludge Treatment", in Physicochemical Processes for Water Quality Control. W.J. Weber, Jr. (ed.), Chap. 12, pp. 559-563. Wiley-Interscience, 1972.

Eckenfelder, W.W., Jr. and Ford, D.L., Water Pollution Control, Jenkins Book Publishing Co., Austin and New York, Chapter 5, 1970.

Eckenfelder, W.W., Jr., et al., "Studies on Dissolved Air Flotation of Biological Sludges", In Biological Treatment of Sewage and Industrial Wastes, Vol. 2., J. McCabe and W.W. Eckenfelder, Jr. (ed.), pp. 251-259, Reinhold, 1958.

Eliassen, R. and Schulhoff, H.B., "Grease Removal by Vacuum Flotation", Sew. Works Jour. 16(2):287, 1944.

Ettelt, G.A., "Activated Sludge Thickening by Dissolved Air Flotation", Proc. 19th Ind. Waste Conf., Purdue Univ. Ext. Ser. 117:1, 210-244, 1964.

Ettelt, G.A., and Kennedy, T.J., "Research and Operational Experience in Sludge Dewatering at Chicago", Jour. W.P.C.F., 38(2):248, 1966.

Gehr, R. and Henry, J.G., "Laboratory Techniques for Evaluating Batch Flotation of Activated Sludge", Wat. Poll. Res. in Canada, 11, 19-33, 1976.

Gehr, R. and Henry, J.G., "Measuring and Predicting Flotation Performance", Jour. WPCF, 50(2):203-215, 1978.

Gupta, M.K. and Agnew, R.W., "Two Wisconsin Cities Treat Combined Sewer Overflows", Wat. and Sew. Works, 120(8):49, August, 1973.

Hansen, C.A., and Gotaas, H.B., "Sewage Treatment by Flotation", Sewage Works Journal 15(2):242, 1943.

Hay, T.T., "Air Flotation Studies of Sanitary Sewage", Sew. and Ind. Wastes, 28(1):100, 1956.

Hemming, M.L., et al., "Experiences in the Treatment of Domestic Sewage by the Microflotation Process", paper presented at the Flotation for Water and Waste Treatment Conference, Water Research Centre, Felixstowe, England, June, 1976.

Hopper, S.H. and McCowen, M.C., "A Flotation Process for Water Purification". Jour. AWWA, 4(8):719-726, August, 1952.

Howe, R.H.L., "A Mathematical Interpretation of Flotation for Solids-Liquid Separation", in Biological Treatment of Sewage and Industrial Wastes, Vol. 2, J. McCabe and W.W. Eckenfelder Jr. (ed.), pp. 241-250, Reinhold, 1958.

Huether, R., "Primary Treatment of Raw Sewage by Dissolved Air Flotation", paper prepared for Wastewater Technology Centre, Environment Canada, Burlington, Ont., and Univ. of Western Ontario, December, 1974.

Hyde, R.A., et al., "Water Clarification by Flotation", Jour. AWWA, 69(7):369-374, July, 1977.

Jank, B.E., et al., "Activated Sludge Treatment of Airport Wastewater Containing Aircraft De-Icing Fluids", Wat. Res. 8, 875-880, 1974.

Jones, W.H., "Sizing and Application of D.A.F. Thickeners", Wat. and Sew. Works, Ref. no. PR177, Nov. 1968.

Kalinske, A.A., "Flotation in Waste Treatment", In: Biological Treatment of Sewage and Industrial Wastes, Vol. 2, J. McCabe and W.W. Eckenfelder Jr. (ed.), pp. 222-231, Reinhold, 1958.

Kalinske, A.A. and Evans, R.R., "Comparison of Flotation and Sedimentation in Treatment of Industrial Wastes", Proc. 8th Ind. Waste Conf. Purdue Univ., 1953.

Katz, W.J., "Operators Forum", Jour. W.P.C.F. 36(4):407-416, April, 1963.

Katz, W.J. and Geinopolos, A., "Sludge Thickening by Dissolved Air Flotation", Jour. W.P.C.F. 39(6):946-957, 1967.

Kemp, G., Komline-Sanderson Ltd., personal communication, 1976.

Knapton, R.C. and Taylor, A.R., "New Flotation System Really Cuts Solids", Water and Wastes Eng. 12, 8, 1975.

Komline, T.R., "Sludge Thickening by Dissolved Air Flotation in the U.S.A.", paper presented at the Flotation for Water and Waste Treatment Conference, WRC, Felixstowe, England, June, 1976.

Kormanik, R.K., "Factors Influencing Batch Flotation Tests - Discussion", Jour. W.P.C.F. 46(8) 2056, 1974.

Laboon, J.F., "Experimental Studies on the Concentration of Raw Sewage", Sew. and Ind. Wastes 24 (4):423, 1952.

Leininger, K.V. and Wall, D.J., "Available Air Measurements Applied to Flotation Thickener Evaluations", Deeds and Data, W.P.C.F. 11(5), May, 1974.

Levy, R.L., et al., "Treatment of Combined and Raw Sewages with the Dissolved Air Process", Water Research 6, 1487-1500, 1972.

McMichael, W.F., "Cost of Dissolved Air Flotation Thickening of Waste Activated Sludge at Municipal Sewage Treatment Plants", Nat. Env. Res. Centre, February 1974, distributed by Nat. Tech. Inf. Ser. U.S. Dept. of Commerce, PB 226 582.

Mennel, M., et al., "Treatment of Primary Effluent by Lime Precipitation and Dissolved Air Flotation", Jour. W.P.C.F. 46(11):2471-2485, 1974.

Mulbarger, M.C. and Huffman, D.D., "Mixed Liquor Solids Separation by Flotation", Jour. San. Eng. Div. ASCE 96, SA4, 861, August , 1970.

Parsons, W.A., "Activated Sludge Effluent Polishing", Proc. 32nd Annual Ind. Waste Conf., Purdue Univ., p. 24, May, 1977.

Rich, L.F., Unit Operations of Sanitary Engineering. Wiley & Sons, Inc. (1961). Chap. 5: Flotation and Aerosol Separation.

Sandbank, E., "Improved Electroflotation for the Removal of Suspended Solids from Algal Pond Effluents", Water Research 8: 587-592, 1974.

Snider, I.F., Jr., "Algae Removal by Air Flotation", paper presented at the Ponds as a Wastewater Treatment Alternative Conference, Centre for Research in Water Resources, University of Texas at Austin, July 22-24, 1975.

Speece, R.E., et al., "Application of a Low Energy Pressurized Gas Transfer System to Dissolved Air Flotation and Oxygen Transfer", Proc. 30th Purdue Industrial Waste Conference, p. 465, May 1975.

Stander, G.J. and van Vuuren, L.R.J., "Flotation of Sewage and Waste Solids", in Water Quality Improvement by Physical and Chemical Processes, Water Resources Symposium No. 3, University of Texas Press, E.F. Gloyna and W.W. Eckenfelder, Jr. (ed.), p. 190. 1970.

Turner, M.T., "The Use of Dissolved Air Flotation for the Thickening of Waste Activated Sludge", Effl. and Wat. Treat. Jour., 15 (5): May 1975. (British).

U.S. Environmental Protection Agency, "Process Design Manual for Sludge Treatment and Disposal", EPA 625/1-74-006, 1974.

Valiquette, Y., "Dissolved Air Flotation for Woodroom Effluent Treatment", Pulp and Paper Canada, 77(3):71-74, March, 1976.

Van Vuuren, L.R.J. et al., "Dispersed Air Flocculation/Flotation of Organic Pollutants from Effluents", Water Research 2: 177-183, 1968.

Vrablik, E.R., "An Evaluation of Circular Gravity-Type Separation and Dissolved-Air Flotation for Treating Oil Refinery Waste Water", Proc. 12th Ind. Waste Conf., Purdue Univ., p. 73, 1957.

Vrablik, E.R., "Fundamental Principles of Dissolved-Air Flotation of Industrial Wastes", Proc. 14th Ind. Waste Conf., Purdue Univ., 743, 1959.

Walzer, J.G., "Dissolved Air Flotation in the Waste Activated Sludge Process", The Permutit Company, Inc., October, 1975.

White, R.L. and Cole, T.G., "Dissolved Air Flotation for Combined Sewer Overflows", Public Works, 104(2): 50-54, February, 1973.

Wood, R.F., "The Effect of Sludge Characteristics Upon the Flotation of Bulked Activated Sludge", Univ. of Illinois at Urbana-Champaign, Ph.D. Thesis, 1970. University Microfilms, 71-15,003.

Wood, R.F. and Dick R.I., "Factors Influencing Batch Flotation Tests", Jour. W.P.C.F. 45(2): 304-315, 1973.

Wood, R.F. and Dick, R.I., "Some Effects of Sludge Characteristics on Dissolved Air Flotation", paper presented at the 7th Int. Conf. on Wat. Poll. Res., Paris, September, 1974.

Zabel, T.F. and Rees, A.J., "The W.R.C. Flotation Working Group's 2300 m^3/day Pilot Plants", paper presented at the Flotation for Water and Waste Treatment Conference, Water Research Centre, Felixstowe, England, June, 1976.

APPENDIX A
SYMBOLS AND ABBREVIATIONS

APPENDIX A. SYMBOLS AND ABBREVIATIONS

List of Symbols and Abbreviations Not in Standard Use

A/S	air to solids ratio
abs	absolute
atm	atmosphere
CAS	conventional activated sludge
DAF	dissolved air (pressure) flotation
EA	extended aeration
Eff. TT	effective times thickening = $\frac{\text{Float TS (mg/L)}}{\text{Total solids (mg)/Total vol. (L)}}$
F/M	food to microorganism ratio ($days^{-1}$)
H_0:	the null hypothesis is.....
Inf.	influent
L.R.	linear regression
MLSS	mixed liquor suspended solids (mg/L)
RS	raw sewage
Sol P	soluble phosphorus (mg/L)
TP	thickening parameter = $\frac{\text{Eff. TT}}{\text{A/S}}$
TS	total solids (%)
σ	standard deviation

APPENDIX B
DISSOLVED AIR MEASUREMENTS

APPENDIX B DISSOLVED AIR MEASUREMENTS

B.1 Batch Method for Determining the Percentage Saturation of Air in Recycle DAF Liquid (After Komline-Sanderson)

The procedure below is recommended for determining the volume of air dissolved in the liquid in the retention tank of a DAF unit (see Figure B1).

Equipment List:

1 - 4000 mL beaker
1 - 500 mL graduated cylinder
1 - small valve
1-m - long plastic tubing
1 - thermometer
1 - barometer

The 500 mL graduated cylinder provides a large enough volume to enable the released air volume to be read to an accuracy of about 2 mL.

Procedure:

1) Allow DAF unit to reach steady state operation.
2) Fill the graduated cylinder to the top, and the beaker with about 2 L of water.
3) Invert the cylinder, placing the palm of the hand over its mouth to prevent water from escaping, and place the inverted cylinder into the partially filled beaker. When the palm is removed, a vacuum will be formed above the water in the graduated cylinder.
4) Mark the water level in the beaker as B.
5) Add exactly 1 L of water to the beaker, and mark this second level A.
6) Pour out the water in the beaker to the original mark B, taking care not to permit air to enter the cylinder.
7) Record the volume of the vacuum in the cylinder.
8) Record all relevant operating conditions, such as temperature, pressure (atmospheric and retention tank) and flow rates.
9) Crack open the valve, and allow aerated water to enter the cylinder, as shown in Figure C1. The flow should be slow enough that air bubbles do not leak out and around the bottom of the cylinder.

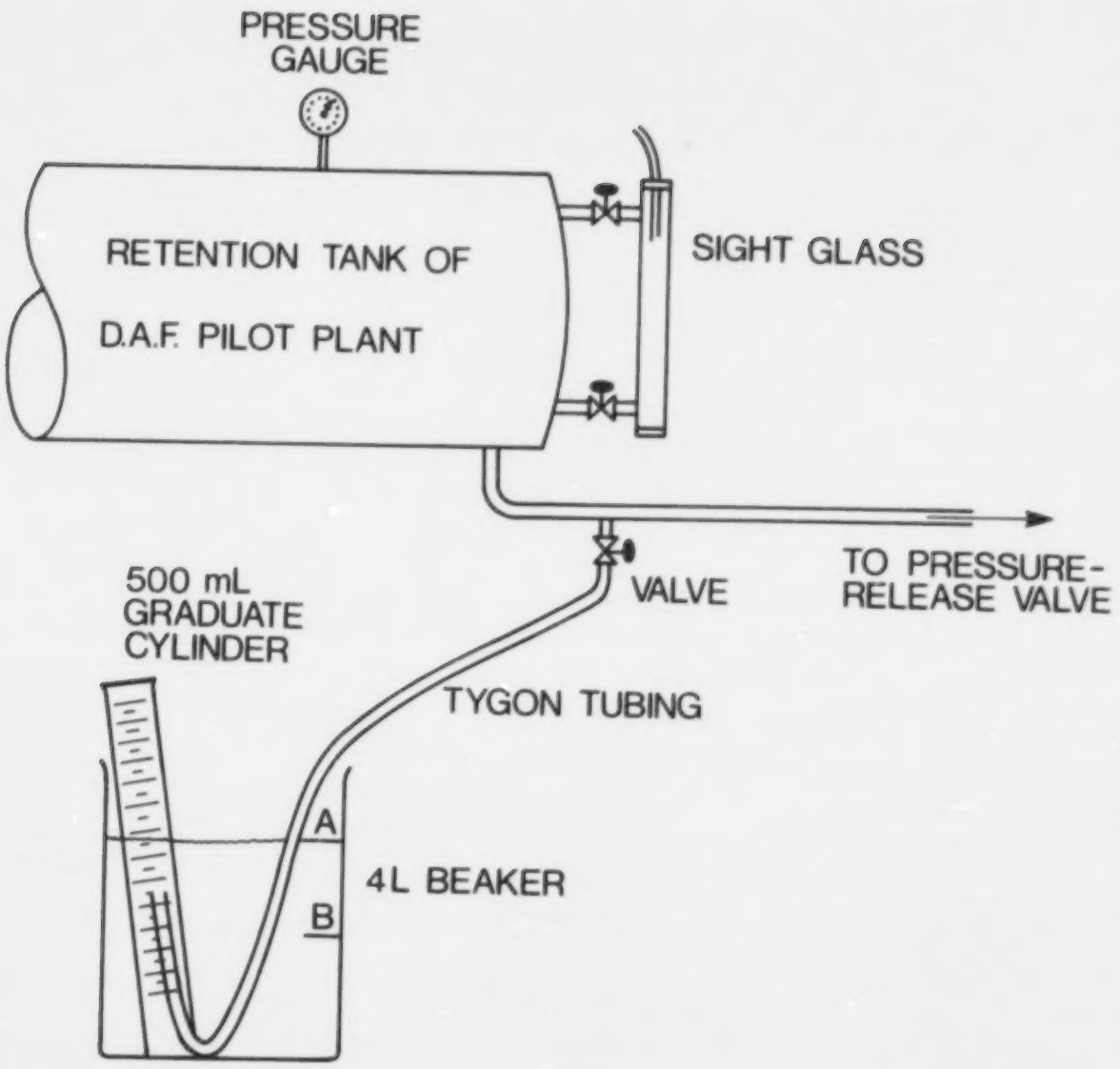


FIGURE B1 EQUIPMENT ARRANGEMENT FOR MEASURING DISSOLVED AIR IN DAF PILOT PLANT (batch method)

10) Close the valve when the water level reaches mark A.

11) When all the air bubbles have escaped from solution and the liquid in the cylinder is clear again, record the volume of air in the top of the graduated cylinder.

Calculation:

$$\text{Percent saturation} = \frac{V_r \times 100}{V_s}$$

where: V_r = volume of air at 21°C released per L of pressurized water (mL)

$$= \frac{1000\ V_e}{1000 - V_e} \times \frac{294}{t + 273} \times \frac{p}{760}$$

V_e = volume of air trapped in graduated cylinder (mL)

t = temperature of liquid (°C)

p = atmospheric pressure (mm Hg)

V_s = volume of air at 21°C theoretically releasable at atmospheric pressure from 1 L of water saturated with air at the retention tank operating temperature.

$$= V_{760} \times \frac{P}{760} \times \frac{294}{t + 273} \times P$$

V_{760} = air solubility at 1 atmosphere (see Table B1 below)

P = retention tank gauge pressure (atm.)

TABLE B1 SOLUBILITY OF AIR IN WATER

	Temperature (°C)											
	10	11	12	13	14	15	16	17	18	19	20	21
Dissolved wet air volume (mL/L)	22.84	22.34	21.87	21.41	20.97	20.55	20.14	19.75	19.38	19.02	18.68	18.34

B.2 DO Meter Method for Determining the Percentage Saturation of Air in Recycle DAF Liquid

Equipment:

A Beckman Model 7002 Oxygen monitor was used in the routine determination of percentage air saturation in the recycle. This meter has the following features which enable it to be used under the experimental conditions:

1) Dissolved oxygen is measured by weight.
2) Temperature compensation exists through the range 0 to 45°C
3) Pressure equalization up to 345 kPa is provided.
4) The orientation of the probe does not affect accuracy.
5) The probe can be used under pressure in a flow-through chamber.
6) Accuracy of plus/minus one percent over the full range is claimed.

The meter was modified to enable a range of 0 to 40 mg/L O_2 to be read.

Procedure:

A DO reading was taken simply by plugging in the meter, and allowing part of the recycle to flow through the by-pass line. The DO value was taken after about 15 minutes, and the by-pass line then shut to avoid damaging the probe membrane.

Calculations:

The effect of varying barometric pressure was neglected. This variation of not more than plus/minus 10 mm Hg in 760 mm Hg would contribute an error of less than two percent. Another assumption was that the percentage oxygen saturation was equal to the percentage air saturation.

$$\text{Then, percent saturation} = \frac{O_1}{O_2} \times 100$$

where: O_1 = DO meter reading (mg/L)

O_2 = theoretical saturated DO at the retention tank pressure (mg/L)

$= O_{atm} \times P_{abs}$

O_{atm} = DO at atmospheric pressure, from Table B2 below

P_{abs} = absolute pressure in the retention tank (atm)

Table B2 SOLUBILITY OF OXYGEN, NITROGEN AND AIR IN WATER

	Temperature (°C)														
	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
O_2 (mg/L)	11.3	11.1	10.8	10.6	10.4	10.2	10.0	9.7	9.5	9.4	9.2	9.0	8.8	8.7	8.5
N_2 (mg/L)	18.9	18.5	18.0	17.6	17.2	16.8	16.4	16.2	15.9	15.6	15.4	15.1	14.9	14.7	14.5
Air (mg/L)	30.2	29.6	28.8	28.7	27.5	27.0	26.4	25.9	25.4	25.0	24.6	24.1	23.7	23.4	23.0

Two tests were done during phase 1 of this study (flotation of extended aeration mixed liquor) to compare the values of the percentage air saturation obtained by the above mentioned two methods. The results are presented in Table B3 below.

TABLE B3 PERCENT AIR SATURATION. DAF PILOT PLANT, PHASE 1

Test	Temp (°C)	Retention Tank Gauge Pressure (kPa)	Percentage Saturation	
			Batch Method	DO Meter Method
1	16	386	55	65
2	16	386	62	66

Thus, the two methods give similar results. The DO meter method is understandably higher than the batch method because some air bubbles are inevitably lost when inverting the graduated cylinder in the batch method. The results show conclusively, however, that percent saturation is substantially below the 90 percent value claimed by the manufacturer. The values for saturation in the above table, i.e., about 65 percent or less were measured consistently throughout this study.

APPENDIX C
SUMMARY OF TRACER STUDIES

TABLE C1 SUMMARY OF TRACER STUDIES, DAF PILOT PLANT

Test	Tank Area (m^2)	Inflow (L/min)	Recycle (L/min)	Short circuiting peak time (min)	main peak time (min)	Theoretical peak time (min) (for plug flow)	Ratio	Main peak concentration (ppb)	Theoretical peak concentration (ppb) (for complete mix)	Ratio
1	1.29	68	64	2.1	10.3	27.1	0.38	98	86.2	1.14
2	"	68	73	1.5	5.5	27.1	0.20	126	129.6	0.97
3	"	145	127	2.2	4.0	12.7	0.31	58	45.2	1.28
4	"	145	123	1.2	5.0	12.7	0.39	83	86.2	0.96
5	0.875	45	45	N/A	6.3	22.4	0.28	165	140	1.18
6	"	86	100	"	4.0	11.8	0.33	overflow	187	>1.10
7	"	86	100	"	4.0	11.8	0.33	106	93	1.14
8	"	114	114	"	3.4	9 0	0 38	172	140	1.23

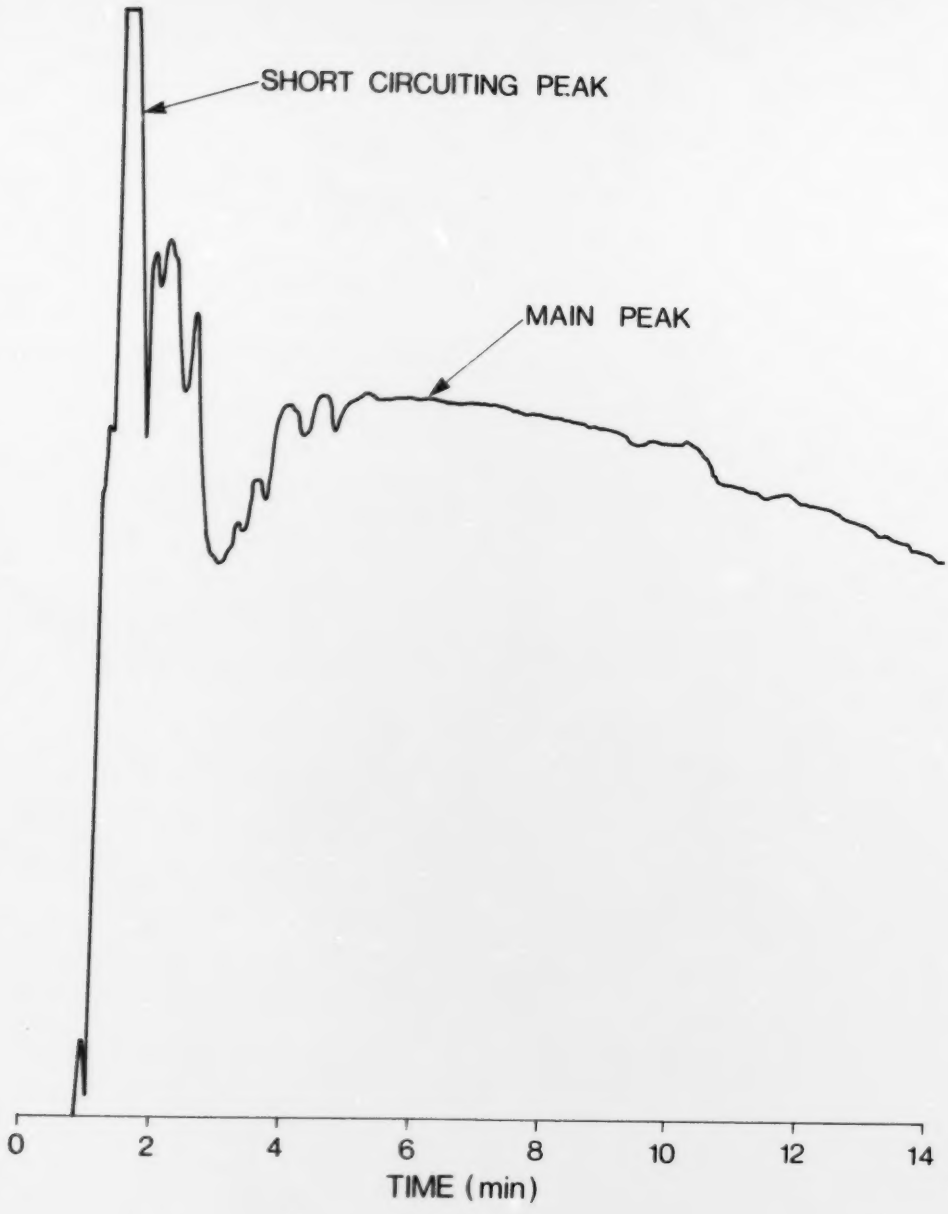


FIGURE C1 TRACER RESPONSE ON ORIGINAL DAF TANK, SHOWING SHORT CIRCUITING AND MAIN PEAKS. TEST 2

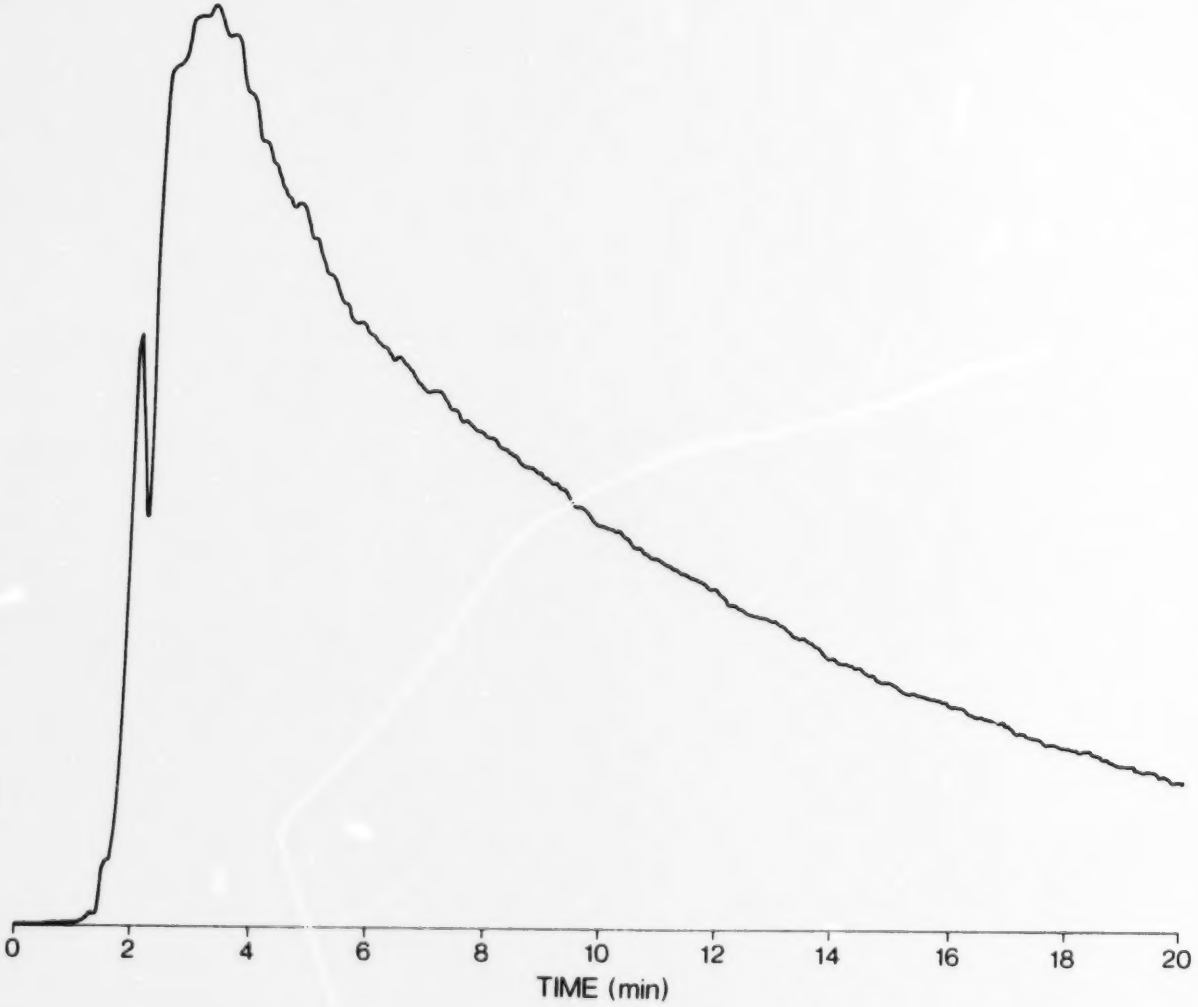


FIGURE C2 TRACER RESPONSE ON MODIFIED DAF TANK. TEST 8

APPENDIX D
JAR TEST RESULTS

APPENDIX D JAR TEST RESULTS

TABLE D1 PHASE 1 JAR TESTS

Chemical	Test	Chemical Dose (mg/L)	Total Phosphorus (mg/L)	Total Soluble Phosphorus (mg/L)
Alum	Mixed Liquor		98	3.7
	1	60	2.2	0.1
	2	120	1.0	0
	3	150	0.1	0
	4	180	0.1	0
	5	240	0.1	0
	Control	0	2.9	2.8
Ferric Chloride	Mixed Liquor		--	2.1
	1	5	2.2	1.9
	2	10	1.9	1.8
	3	15	2.0	1.7
	4	20	1.8	1.7
	5	40	1.0	1.0
	Control	0	2.6	2.6
	Mixed Liquor		--	1.7
	6	60	0.2	0.1
	7	120	0.2	0.1
	8	150	0.2	0.1
	9	180	0.1	0.1
	10	240	0.1	0.1
	Control	0	1.6	1.6
Lime	Mixed Liquor		--	1.4
	1	60	1.6	1.0
	2	120	1.0	0.3
	3	150	1.0	0.3
	4	180	1.0	0.3
	5	240	0.8	0.3
	Control	0	1.4	1.4

TABLE D2 PHASE 2 JAR TESTS

Chemical	Test	Chemical Dose (mg/L)	Total Phosphorus (mg/L)	Total Soluble Phosphorus (mg/L)
Alum	Raw Sewage		5.6	3.0
	1	60	1.1	0.4
	2	120	0.5	0.5
	3	150	0.5	0.3
	4	180	0.2	0.3
	5	240	0.1	0.4
	Control	0	3.0	3.0
Ferric Chloride	Raw Sewage		4.1	1.7
	1	15	1.6	1.2
	2	25	1.3	1.0
	3	35	1.0	0.6
	4	45	0.7	0.3
	5	65	0.6	0.2
	Control	0	3.6	1.6
Lime	Raw Sewage		2.6	1.5
	1	60	0.7	0.4
	2	120	0.5	0.4
	3	150	0.3	0.3
	4	180	0.3	0.2
	5	240	0.1	0.1
	Control	0	0.3	0.3

TABLE D3 PHASE 3 JAR TESTS

Chemical	Test	Chemical Dose (mg/L)	Total Phosphorus (mg/L)	Total Soluble Phosphorus (mg/L)
Alum	Mixed Liquor		20	0.8
	1	60	0.4	0.3
	2	120	0.2	0
	3	150	0	0
	4	180	0	0
	5	240	0	0
	Control	0	1.0	0.7
Ferric Chloride	Mixed Liquor		23	0.8
	1	10	0.4	0.1
	2	25	0.1	0
	3	40	0.1	0
	4	50	0	0
	5	60	0	0
	Control	0	0.8	0.7

The Cost of Phosphorus Removal Chemicals

The following table of chemical costs is based on 1977 average costs pertaining to southern Ontario:

Chemical	¢/kg (dry)	Ratio, based on Lime = 1.0
Ferric Chloride	18.8	5.70
Alum	10.4	3.15
Lime	3.3	1.00

Lime is clearly the cheapest chemical, even if the higher dosage requirements are taken into account. However, the practical problem of pumping lime slurries were considered a sufficient basis for rejection. On the basis of dosage required for equal amounts of phosphorus removed, ferric chloride is slightly cheaper than alum.

APPENDIX E
SAMPLE CALCULATIONS AND APPLICATION OF THE THICKENING PARAMETER AND THICKENING EQUATION

E.1 Sample Calculations for Experiments (Test 1, Phase 3. Pilot Plant)

Influent Details:

Source:	Conventional Activated Sludge Mixed Liquor	
MLSS:	2616 mg/L	(1)
Total P:	12.0 mg/L as P	(2)
TSP:	0.8 mg/L as P	(3)

Chemical Addition:

Type:	$FeCl_3$	
Quantity:	28 ml/min @ 4%	(4)

Polymer Addition:

Type:	Percol 728	
Quantity:	120 ml/min @ 0.1%	(5)

Operating Details:

Temperature:	13.5°C	
Pressure:	380 kPa = 3.76 atm	(6)
Recycle flow:	77.3 L/min	(7)
Influent flow:	45.5 L/min	(8)
DO:	34 mg/L	(9)
Skimmer:	8 min on, 2 min off	

Effluent Details:

SS:	25 mg/L	(10)
Total P:	0.3 mg/L	(11)
TSP:	0.2 mg/L	(12)

Float Details:

TS:	69 790 mg/L	(13)

Calculations:

Total Influent solids $= 1 \times 8$

$= 119\,000$ mg/min (14)

Chemical dose $= \dfrac{4 \times 10^{-3} \times 4.0 \times 10^{4}}{8}$

$$= 25 \text{ mg/L}$$

$$\text{Polymer dose} = \frac{5 \times 10^3}{17} = 1.0 \text{ mg/L}$$

Saturated DO @ 13.5°C and 1 atm = 10.5 mg/L (from Table B2) (15)

Theoretical sat. DO @ operating pressure $= 15 \times (6 + 1.0)$ (16)

$= 50.0$ mg/L

$$\text{Saturation} = \frac{9}{16}$$

$= 0.68$ or 68% (17)

Saturated DN @ 13.5°C and 1 atm = 1.74 mg/L (from Table C2) (18)

Saturated D. Air @ 13.5°C and 1 atm = 27.9 mg/L (from Table B2) (19)

Available air for flotation is

(total air dissolved at operating pressure - air remaining at 1 atm) x recycle flow

$= \{[9 + 17 \times 18 \times (6 + 1.0)] - 19\} \times 7$

$= 4830$ mg/min (20)

$$\text{A/S:} = \frac{20}{14}$$

$= 0.0406$ (21)

Effective influent solids concentration is

$$\frac{\text{(total mass of solids entering tank)}}{\text{(total volume of liquid entering tank)}}$$

$$= \frac{14}{(7 + 8)} = 969 \text{ mg/L} \quad (22)$$

Effective times thickening is

$$\frac{\text{(float solids concentration)}}{\text{(effective influent solids concentration)}}$$

$$= \frac{13}{22}$$

$= 72.0$ (23)

Thickening parameter is

$$\frac{\text{(effective times thickening)}}{\text{(A/S)}}$$

$$= \frac{23}{21}$$

$$= 1773$$

$$\text{SS reduction} = \frac{1 - 10}{1} \times 100$$

$$= 99.0\%$$

$$\text{Total P reduction} = \frac{2 - 11}{2} \times 100 = 97\%$$

$$\text{TSP reduction} = \frac{3 - 12}{3} \times 100 = 75\%$$

Hydraulic load, for 0.836 m^2 surface area

$$= \frac{8 \times 10^{-3} \times 60.0}{0.836}$$

$$= 3.24 \text{ m/h}$$

$$\text{Solids load} = \frac{14 \times 10^{-6} \times 60}{0.836}$$

$$= 8.54 \text{ kg/m}^2\text{•h}$$

E.2 Application of the Thickening Parameter and Thickening Equation

As described in Section 7 the thickening parameter (TP) was originally developed as an improvement on the A/S ratio, which was in general use as a measure of flotation performance. The TP can be expressed in two ways:

$$TP = \frac{\text{effective times thickening}}{A/S} = \frac{\left(\frac{\text{Flotation concentration}}{\text{Effective influent SS}}\right)}{A/S}$$

or $$TP = \frac{F(V_s + V_r)}{A}$$

where: F = concentration of float

V_s = sludge (influent) volume

V_r = recycle volume

Thus, the TP is independent of influent solids concentration. If TP is a constant for a particular waste without flotation aids it may be used:

a) to quantify the flotability of a particular waste (the higher the TP, the thicker the float for a given quantity of air, and the more amenable the waste is to flotation thickening);

b) to assess the effects of flotation aids (the aid yielding the highest TP would be best, assuming favourable economics exist as well);

c) to design the air requirements of a full-scale system from batch experiments. Experiments in phases 1 and 3 showed that TP values for optimum conditions for batch and pilot plant tests were within approximately 20 percent of each other and that the batch tests gave conservative values. Thus, in practice, once the TP was obtained by experiment with the particular waste to be treated, V_s, V_r, and A could be determined depending on the desired float concentation F.

Implied in the calculation of TP is the fact that a graph of effective times thickening vs. A/S passes through the origin. This has been found to be true in some cases, but statistically questionable in others. Linear regression, however, was always acceptable within experimental error; even in Phase 2, with a wide scatter of influent solids concentration values, linear regression was higher than 0.7 (Figure 20). In cases where the graph of effective times thickening vs. A/S does not pass through the origin, TP values would have a wide scatter, and it would be preferable to use a thickening equation (TE) for design or prediction purposes. The TE is the linear regression equation of the plot of effective TT vs. A/S. Once this equation has been established from experiments, it may be used for prediction or design in a similar way to the TP. In this case, however, the influent solids concentration forms part of the equation, and it must be assumed before float concentration and/or air requirements can be determined. The designer or plant operator would have to decide whether use of the TP rather than that of the TE is justified. Obviously, the TP has wider application because it is independent of influent solids concentration.

Both the TP and the TE apply only to designing the air requirements for obtaining a certain float solids concentration. A similar parameter for effluent solids concentration did not give usable results. The TP and TE do not cover area and volume requirements of the flotation tank. The rise has been used historically to determine these quantities from batch tests, but the authors have found the determination of rise rate to

be problematical and the results inconsistent and it is their recommendation that pilot plant tests be done for ascertaining these parameters.

E.3 Design Example

This section explains how information about the thickening behaviour of a particular sludge is used to determine the required A/S ratio.

Methodology:

1) Batch tests:

   a) Determine thickening parameter or thickening equation for the waste without flotation aids.
   b) Choose chemical type and dose for highest TP or steepest slope of TE and/or lowest effluent solids concentration.

2) Pilot tests:

   a) Confirm TP or TE and chemical dose.
   b) Determine optimum solids or hydraulic load.
   c) Determine optimum float removal procedure.

Alternatively, use TP or TE from batch tests, and obtain solids or hydraulic load from manufacturer.

3) a) Size full-scale unit using solids or hydraulic load.
   b) Determine maximum amount of air and hence recirculation rate needed from TP or TE for required float concentration.
   c) Chemical dose is taken from 1 or 2.

Example:

45 500 m^3/d conventional activated sludge plant (see also Appendix K)
Thickening equation: (See Figure 23)

$$y = 1490 x + 13$$

where y = effective times thickening

$$x = A/S$$

Inflow = 4.5×10^6 L/d
Influent SS = 2900 (mg/L)
Float TS = 6.0% (desired) = 60 000 (mg/L)
Recirculation flow = r x 10^6 L/d (r = (ML/d))

Effective influent solids concentration $= \dfrac{2900 \times 45 \times 10^6 \text{ (mg/d)}}{(45 + r) \times 10^6 \text{ (L)}}$

$= \dfrac{130\,000}{(45 + r)} \quad \left(\dfrac{\text{mg}}{\text{L-d}}\right)$

$\therefore y = \dfrac{\text{float TS}}{\text{effective infl. solids conc.}}$

$= \dfrac{60\,000 \times (45 + r)}{130\,000}$

$= 0.4598\,(45 + r)\,(d)$

$x = \dfrac{A}{S}$

where A = air supplied by recycle (mg/d)

$= [(O_p + PN_\theta) - (O_\theta = N_\theta)]\, r \times 10^6$ (θ = operating temperature)

Let temperature = 20°C

then O_θ = 9.2 mg/L)

N_θ = 15.4 (mg/L)

f = efficiency of eductor

= 0.6 (assumed)

Assume gauge pressure = 410 kPa

= 4.1 atm

$\therefore$ P = 4.1 + 1 = 5.1 atm.

O_p = 5.1 x 9.2 x 0.6 (Normally O_p would be measured)

$\therefore$ A = $[5.1 \times 0.6\ (9.2 + 15.4) - (9.2 + 15.4)]\, r \times 10^6$

= $\underline{50.68\, r \times 10^6 \text{ (mg/d)}}$

S = $4.5 \times 10^6 \times 2900$

= $\underline{1.305 \times 10^{11} \text{ (mg/d)}}$

$\therefore \quad x = \dfrac{A}{S} = \dfrac{50.68\, r \times 10^6}{1.305 \times 10^{11}} = \underline{38.84\, r \times 10^{-5}}$

$\therefore$ from y = 1490 x + 13

$$0.4598\,(45 + r) = 1490\,(38.84\,r \times 10^{-5}) + 13$$

$$20.69 + 0.4598\,r = 0.5787\,r + 13$$

$$\therefore \quad 0.1189\,r = 7.69$$

or $r = 64.68$ (ML/d)

say $r = \underline{65 \text{(ML/d)}}$

or recycle ratio $= \frac{65}{45} = \underline{1.44}$

Hence, $A/S = 38.84 \times 65 \times 10^{-5}$

$= \underline{0.025}$

Note: Power calculations for phase 3 (in Table K2) used a recycle ratio of 1.5 and A/S of 0.026.

APPENDIX F
SUMMARY OF POLYMERS USED

APPENDIX F
SUMMARY OF POLYMERS USED

Manufacturer	Type		Activity	Form
Allied Colloids	Percol	720	non-ionic	Powder
(Canada) Ltd	"	722	Medium cationic	micro-bead
	"	725	Medium anionic	Powder
	"	726	high anionic	Powder
	"	728	medium cationic	Powder
	"	730	low anionic	Powder
	"	744	v. high cationic	liquid 15%
	"	751	v. high cationic	liquid 20%
	"	757	high cationic	micro-bead
	"	763	high cationic	micro-bead
	"	776	high cationic	micro-bead
Hercules Inc.	Hercofloc	812	low cationic	Powder
	"	815	medium cationic	Powder
	"	818	low anionic	Powder
	"	831	medium anionic	Powder
	"	834	high cationic	liquid, 15%
	"	849	mdm-high cationic	Powder
	"	855	mdm-high cationic	Powder
Calgon Canada	Cat-Floc-A		Medium cationic	liquid, 12%
	E-207L		low cationic	liquid, 6%
	M-540		medium cationic	liquid, ?
	M-600		anionic	liquid, ?
	WT-2690		non-ionic	Powder
	WT-2870		strong cationic	liquid, ?
	WT-3000		anionic	Powder

Note: "liquid, 15%" means a polymer with 15% active solids.

APPENDIX G
RESULTS OF BATCH TESTS

APPENDIX G RESULTS OF BATCH TESTS

TABLE G1. OPTIMUM A/S DETERMINATION. DAF BATCH FLOTATION UNIT, PHASE 1

Test	Influent SS (mg/L)	Pressure (Pa)	Recycle Ratio	Effluent SS (mg/L)	Float TS (%)	Air Sat. (%)	A/S x 100	TP	SS reduction (%)
1	5687	345	1.97	39	4.42	80.3	2.45	943	99.3
2	6431	345	0.93	55	4.29	87.2	1.15	1124	99.1
3	5546	276	1.34	53	4.20	98.5	1.80	988	99.0
4	5311	310	1.28	36	4.56	81.0	1.49	1313	99.3
5	5292	310	1.97	89	4.69	86.3	2.61	1008	98.3
6	5292	310	0.93	51	4.16	88.0	1.31	1158	99.0
7	4940	207	1.43	65	3.95	95.8	1.58	1231	98.7
8	6122	207	1.70	51	3.88	96.0	1.51	1136	99.2
9	6413	207	2.20	33	4.25	99.3	1.91	1107	99.5
10	6239	207	2.51	37	4.34	99.3	2.23	1095	99.4
11	6239	207	0.67	11	3.58	98.3	0.62	1552	99.9

TABLE G2. BATCH TESTS WITH POLYMER. CHOICE OF POLYMER, AND OPTIMUM POLYMER DOSE, PHASE 1

Test	Influent SS (mg/L)	Pressure (kPa)	Recycle Ratio	Polymer Type	Dose mg/g	Effluent SS (mg/l)	Float TS (%)	Air Sat (%)	A/S x 100	TP	SS red (%)	Test cost ¢/kg solids
1	5954	207	2.51	Hercofloc 849	1.05	29	3.89	94.3	1.9	1209	99.5	0.603
2	5954		2.51	Percol 744	1.05	20	3.94	95.7	2.00	1162	99.7	0.557
3	4475		1.77	Hercofloc 834	0.656	5	1.85	97.0	2.13	536	99.9	
4	4475			Percol 728	0.99	10	2.53	91.0	1.93	811	99.8	0.408
5	4747			Calgon WT2870	0.28	16	1.62	96.0	1.97	479	99.7	0.122
6	4747			Calgon E2607	0.056	50	2.04	94.2	1.89	628	98.9	0.053
7	3969		1.81	-	-	72	1.88	95.3	2.35	565	98.2	-
8	4404		1.77	Percol 757	1.00	-	3.76	91.0	1.93	1224	-	0.448
9	5599		1.77	Calgon cat flocA	0.757	-	3.90	92.2	1.57	1227	-	0.416
10	5488		2.24	Percol 751	1.02	27	4.33	92.7	1.99	1287	99.5	0.372
11	3789		2.24	Hercofloc 855	1.48	15	3.58	91.5	2.80	1066	99.6	0.751
12	3819	310	1.97	Percol 728	1.11	32	4.30	86.1	3.68	911	99.2	0.464
13	3819		1.28	Percol 728	0.726	25	4.01	84.6	2.34	1024	99.3	0.301
14	4031		1.28	Percol 744	0.715	41	3.76	90.0	2.11	1010	99.0	0.377
15	4031			Calgon WT2870	0.714	13	4.14	88.0	2.16	1084	99.7	0.314
16	4306			Percol 751	0.64	9	4.10	87.0	2.13	1020	99.8	0.234
17	4306			Percol 757	0.64	7	4.06	87.0	1.99	1080	99.8	0.288
18	8645		1.55	Percol 759	0.39	22	3.58	91.6	1.28	826	99.7	0.174
19	8645			Percol 757	0.75	20	3.63	87.8	1.28	838	99.8	0.335
20	8167			Percol 757	1.27	12	3.33	86.3	1.33	782	99.9	0.568
21	8167			Percol 757	0.26	31	3.59	89.0	1.44	779	99.8	0.116
22	3888			Percol 751	0.87	39	3.71	91.0	2.91	836	99.0	0.316
23	3888			Calgon WT2870	0.84	31	3.90	91.5	3.03	845	99.2	0.370
24	3689			Hercofloc 855	0.91	10	3.72	96.3	3.31	779	99.7	0.460
25	3689			Hercofloc 849	0.91	8	3.66	92.0	3.06	827	99.8	0.521
26	3172			Percol 757	1.06	19	4.10	92.0	3.47	952	99.4	0.474
27	3172			Percol 728	1.06	11	3.78	93.0	3.61	843	99.6	0.439
28	3425		1.11	Percol 757	0.7	5	3.93	94.0	2.44	991	99.9	0.313
29	3425		1.11	Percol 728	0.7	20	3.66	94.0	2.44	921	99.4	0.290
30	3196		1.32	Percol 757	0.89	5	4.15	93.0	3.19	942	99.8	0.397
31	3196		1.32	Hercofloc 849	0.89	5	3.69	90.0	2.99	895	99.8	0.509
32	4048	276	1.11	Percol 757	0.71	-	3.85	92.5	2.04	982	-	0.317
33	4048		1.23	Percol 757	0.71	-	4.11	88.0	1.93	1171	-	0.317
34	3795		1.18	Percol 757	1.55	-	4.15	91.0	2.23	1067	-	0.693

TABLE G3. OPTIMUM A/S DETERMINATION. DAF BATCH FLOTATION UNIT, PHASE 2

Test	Influent SS (mg/L)	Recycle Ratio	Effluent SS (mg/L)	Air Sat. (%)	A/S x 10	SS red (%)	Solids capture (%)
1	391	0.94	79	92.5	1.70	80	67
2		0.69	83	92.5	1.26	79	64
3		0.43	189	96.4	0.875	52	31
4	190	0.69	85	84.0	2.26	55	23
5		0.93	66	90.0	3.43	65	33
6		1.34	57	85.0	4.40	70	30
7		1.97	45	89.0	6.83	76	31

Pressure: Constant at 275 kPa

TABLE G4. OPTIMUM A/S DETERMINATION. DAF BATCH FLOTATION UNIT, PHASE 3

Test	Influent SS (mg/L)	Recycle Ratio	Effluent SS (mg/L)	Float TS (%)	Air sat. (%)	A/S x 100	TP	SS reduction (%)
1	2531	0.924	49	6.94	89	2.82	1887	98.0
2	2531	1.28	57	6.56	91	3.83	1543	97.7
3	2393	1.97	45	6.10	86	5.74	1320	98.0
4	2393	0.43	34	5.94	93	1.27	2794	98.6
5	2713	2.24	77	6.06	88	5.89	1229	97.0
6	2713	0.69	62	6.54	89	1.93	2107	97.7

Pressure: Constant at 275 kPa
TP: Mean = 1813, σ = 585, CV = 0.32

TABLE G5. SELECTION OF POLYMER. DAF BATCH FLOTATION UNIT, PHASE 3

Test	Influent SS (mg/L)	Polymer Type	Relative cost	Dose (mg/g)	Effluent SS (mg/L)	Float TS (%)	Air Sat (%)	A/S x 100	TP	SS reduction (%)
1	2767	Percol 728	0.91	0.84	101	7.42	85	2.87	1966	96.3
2	2767	Calgon WT3000	0.88	0.86	129	6.98	86	2.77	1917	95.0
3	3019	Percol 757	1.00	0.70	130	6.71	86	2.59	1807	95.7
4	3019	Hercofloc 855	1.13	0.61	106	6.60	87	2.57	1791	96.5
5	1902	Percol 720	0.83	1.30	136	5.82	85	4.17	1544	92.8
6	1902	Hercofloc 812	0.76	1.45	86	7.01	91	4.48	1732	95.0
7	2781	Percol 722	0.91	0.83	90	6.20	89	2.89	1624	97.0
8	2781	Calgon WT2690	0.88	0.86	117	6.28	88	2.85	1667	96.0
9	2811	Percol 763	0.93	0.80	95	5.64	88	2.87	1471	96.6
10	2811	Hercofloc 815	0.81	0.92	127	6.72	87	2.77	1818	95.4
11	2716	Percol 776	1.00	0.77	78	6.52	90	3.01	1680	97.0
12	2716	Hercofloc 849	1.27	1.27	85	7.10	89	2.93	1874	97.0

Test	Influent SS (mg/L)	Polymer Type	Dose (mg/g)	Effluent SS (mg/L)	Float TS (%)	Air Sat (%)	A/S x 100	TP	SS reduction (%)
13	3105	Percol 728	0.57	77	6.96	88	2.54	1857	97.5
14	3105	Hercofloc 849	0.43	136	6.74	90	2.63	1475	95.6
15	3212	Percol 728	0.96	113	7.04	87	2.43	1898	96.5
16	3212	Hercofloc 849	0.69	55	6.43	88	2.41	1750	98.3
17	2265	Percol 728	1.66	85	7.18	84	3.27	2040	96.0
18	2265	Hercofloc 849	1.17	125	6.75	86	3.22	1948	94.5

Percol 757 was used as a datum, i.e., relative cost of 1.00. Polymer addition was then based on a dose of 0.70 mg/g, influent SS 3000 mg/L, and recycle ratio 1.1.
Polymer dosage (in mg/g) for the other polymers was set in inverse ratio to the relative cost.

APPENDIX H
DAF PILOT PLANT RESULTS

TABLE H1. NO ADDITIONS. DAF PILOT PLANT, PHASE 2

Test	Recycle Ratio	Air Saturation (%)	A/S x 10	Flow (L/min)	Influent SS (mg/L)	Influent COD (mg/L)	Influent Total P (mg/L)	Effluent SS (mg/L)	Effluent COD (mg/L)	Effluent Total P (mg/L)	Float TS (%)	TP	SS red (%)	COD red (%)	Total P reduction (%)	Hydr load (m/h)	Solids load ($kg/m^2 \cdot h$)
1	1.6	49	2.6	45	235	-	4.3	95	-	3.1	5.9	2513	60	-	28	3.25	0.77
2	1.6	47	5.18	45	110	-	2.3	40	-	1.5	5.37	2450	64	-	35		0.36
3	1.6	45	2.61	45	203	-	5.0	57	-	3.7	3.29	1619	72	-	26		0.66
4	1.6	52	6.94	45	100	-	3.0	10	-	1.3	3.92	1468	90	-	57		0.33
5	1.25	50	1.96	91	237	580	7.1	181	390	5.2	3.96	1922	24	33	27	6.5	1.55
6	1.2	51	3.67	91	129	340	3.5	56	170	2.6	5.81	2681	57	50	26		0.84
7	1.07	51	3.26	91	125	440	5.8	86	300	5.4	3.7	1883	31	117	7		0.82
8	1.23	52	7.5	91	65	-	-	50	-	4.4	6.54	3009	23	-	-		0.42
9	1.04	54	6.67	91	71	160	3.1	41	150	4.3	3.51	1514	42	56	39		0.46
10	0.8	49	1.52	91	206	830	9.3	95	200	4.8	5.67	3273	54	76	48		1.34
11	0.65	58	0.714	91	491	340	9.9	49	680	5.7	5.58	2622	90	-100	42		3.20
12	0.75	56	1.04	91	361	540	6.0	97	240	3.2	6.05	2826	73	56	47		2.35
13	0.8	55	1.82	91	209	550	4.8	54	310	4.8	8.02	3799	74	44	24		1.36
14	0.8	58	5.8	91	72	410	-	42	150	-	7.67	3306	42	63	-		0.47
15	0.8	57	2.43	91	169	380	-	55	190	-	6.33	2776	67	50	-		1.10
16	0.7	56	1.80	91	199	470	-	81	250	-	5.11	2427	59	47	-		1.30
17	0.8	55	1.57	91	242	500	-	-	290	-	5.5	2613	-	42	-		1.58
18	0.8	52	1.39	91	251	540	-	129	340	-	6.2	3208	49	37	-		1.64
21	0.57	55	1.06	109	257	500	-	116	200	-	6.3	3626	55	60	-		2.01
22	0.66	54	0.979	109	314	940	-	235	770	-	7.63	4146	25	18	-		2.46

A/S: Mean x 10 = 3.47, σ x 10 = 2.60

TABLE H2. POLYMER ADDITION. DAF PILOT PLANT, PHASE 2

Test	Dose mg/L	Dose mg/g	FeCl mg/L[3]	Recycle ratio	Air Saturation (%)	A/S x 10	Flow (L/min)	Influent SS (mg/L)	Influent COD (mg/L)	Influent Total P (mg/L)	Effluent SS (mg/L)	Effluent COD (mg/L)	Effluent Total P (mg/L)	Float TS (%)	Float TP	SS red (%)	COD red (%)	Total P reduction (%)	Hydr load (m/h)	Solids load (kg/m^2•h)
23	0.22	0.72	-	0.46	48	0.735	109	255	460	-	32	140	-	4.0	3116	87	70	-	7.8	2.00
24	0.22	0.40	-	0.66	52	0.65	109	461	650	-	332	210	-	4.49	2493	30	68	-		3.61
25	0.22	1.0	-	1.1	56	1.99	91	211	410	4.5	66	466	4.5	3.1	1468	70	-14	-	6.5	1.44
26	0.22	1.27	-	1.1	35	1.16	91	173	450	6.0	79	460	4.9	2.7	2804	54	-2	18		1.13
27	0.22	.067	-	1.1	47	1.09	91	327	680	9.8	95	335	4.9	5.7	3338	71	51	49		2.13
28	0.22	.074	-	1.2	46	1.27	91	299	730	8.1	152	320	4.9	6.75	3908	49	56	40		1.95
29	0.22	0.40	-	1.2	50	1.61	91	278	540	8.0	117	320	4.9	9.1	4509	58	41	55		1.81
30	0.44	2.35	-	1.1	54	2.48	91	187	420	6.1	66	220	3.6	6.0	2713	65	48	41		1.22
31	0.44	1.75	-	0.7	50	1.14	91	252	520	9.1	77	240	5.6	4.7	2812	69	54	38		1.64
32	0.44	2.75	-	1.2	43	2.11	91	160	360	6.7	53	150	4.5	7.1	4597	67	58	33		1.04
33	0.44	1.96	-	1.2	49	1.89	91	225	450	7.6	44	190	4.7	5.4	2786	80	58	38		1.47
34	0.44	3.16	-	1.2	49	3.08	91	139	320	6.5	29	110	3.6	6.0	3081	79	66	45		0.91
35	0.44	2.43	-	1.2	54	2.72	91	181	360	6.4	46	150	4.2	5.1	2261	75	58	34		1.18
36	0.44	0.81	-	1.2	52	0.879	91	544	650	9.0	100	280	4.5	7.8	3593	82	57	50		3.55
37	0.44	1.57	-	1.2	50	1.6	91	280	610	6.4	142	380	5.8	7.58	3729	49	38	9		1.83
38	0.55	2.73	-	1.1	-	-	91	201	380	5.8	65	190	3.7	6.2	-	68	50	36		1.31
39	0.55	1.39	-	0.8	-	-	91	395	660	6.1	233	460	5.1	-	-	41	30	16		2.58
40	0.52	2.0	-	1.02	43	1.18	91	283	530	7.5	91	280	4.5	2.36	1429	68	47	40		1.85
41	0.66	2.49	-	1.57	49	1.57	91	265	500	5.6	61	240	4.2	8.0	4239	77	52	25		1.73
42	0.66	5.55	-	1.25	48	3.5	91	119	380	6.9	37	230	6.2	5.34	2882	69	39	10		0.78
43	0.66	3.38	-	1.0	-	-	91	195	400	-	47	130	3.4	4.95	-	76	68	-		1.27
44	0.88	3.96	-	0.8	46	1.27	91	222	-	7.0	42	-	3.9	6.14	3918	81	-	44		1.45
45	0.88	4.97	-	0.8	50	1.91	91	177	-	-	18	-	-	6.15	3274	90	-	-		1.15
46	0.88	2.26	-	0.8	52	0.927	91	389	-	5.4	95	-	3.1	5.56	2777	76	-	43		2.54

A/S: Mean x 10 = 1.66, σ x 10 = 0.776

TABLE H3. $FeCl_3$ ADDITION. DAF PILOT PLANT, PHASE 2

Test	Dose mg/L	Dose mg/g	$FeCl_3$ mg/L	Recycle ratio	Air Saturation (%)	A/S x 10	Flow (L/min)	Influent SS (mg/L)	Influent COD (mg/L)	Influent Total P (mg/L)	Effluent SS (mg/L)	Effluent COD (mg/L)	Effluent Total P (mg/L)	Float TS (%)	Float TP	SS red (%)	COD red (%)	Total P red (%)	Hydr load (m/h)	Solids load ($kg/m^2 \cdot h$)
47	-	-	24	1.6	49	11.1	45	55	-	0.8	35	-	0.5	1.9	761	47	-	38	3.25	0.18
48	-	-	[illegible]	1.6	50	5.44	45	146	-	2.3	24	-	0.7	1.67	464	84	-	70		0.48
49	-	-	24	1.6	62	18.97	45	48	-	0.6	10	-	0.4	3.40	971	79	-	33		0.16
50	-	-	26	0.72	49	2.81	91	104	140	1.7	28	65	0.3	3.87	2446	73	54	82	6.5	0.68
51	-	-	[illegible]	0.7	52	2.39	91	133	200	2.1	18	120	-	3.15	1691	86	40	99.9		0.87
52	-	-	25	0.7	53	2.25	91	143	220	6.4	147	220	0.3	6.1	3226	-	-	87		0.93
53	-	-	42	0.8	50	1.37	91	238	550	5.7	102	350	5.0	5.45	3031	57	40	14		1.55
54	-	-	42	0.7	53	1.10	91	293	170	3.0	162	130	1.9	3.12	1648	45	24	37		1.91
55	-	-	42	0.8	52	1.02	91	339	700	8.7	141	590	6.5	2.43	1265	58	16	25		2.21
56	-	-	42	0.8	56	6.10	91	64	130	2.7	51	94	1.5	3.87	1783	20	28	44		0.42
57	-	-	51	0.8	59	3.09	91	143	-	1.0	47	-	0.1	1.79	728	67	67	90		0.93
58	-	-	51	0.8	63	0.657	136	677	-	4.6	313	-	3.3	2.69	1088	54	54	28		4.41
59	-	-	20	0.67	35	0.523	136	241	620	5.9	227	600	7.0	7.75	10222	5	3	-19	9.75	2.22
60	-	-	20	0.57	24	0.614	136	323	200	3.5	259	160	3.4	4.58	3617	20	20	3		2.53
61	-	-	20	0.67	45	1.61	136	134	670	7.1	104	600	5.0	4.66	3604	29	10	18		1.02
62	-	-	[illegible]	0.66	47	1.43	136	163	320	5.2	82	80	5.0	8.11	5800	50	44	4		0.80

A/S: Mean x 10 = 3.79, σ x 10 = 4.90

TABLE H6. POLYMER PLUS $FeCl_3$ ADDITIONS. DAF PILOT PLANT, PHASE 2

Test	Dose mg/L	Dose mg/g	$FeCl_3$ mg/L	Recycle ratio	Air Saturation (%)	A/S x 10	Flow (L/min)	Influent SS (mg/L)	Influent COD (mg/L)	Influent Total P (mg/L)	Effluent SS (mg/L)	Effluent COD (mg/L)	Effluent Total P (mg/L)	Float TS (%)	Float TP	SS red (%)	COD red (%)	Total P reduction (%)	Hydr load (m/h)	Solids load ($kg/m^2 \cdot h$)
63	0.88	9.17	51	0.8	54	4.00	91	96	-	0.9	10	-	0	5.07	2377	90	-	100	6.5	0.63
64	0.88	4.81	51	0.8	56	2.21	91	183	-	1.0	18	-	0	3.10	1381	90	-	100		1.19
65	0.88	5.15	51	0.8	61	2.71	91	171	-	4.6	17	-	0.5	4.62	1718	90	-	85		1.11
66	0.18	1.08	27	0.66	49	1.59	109	169	390	-	86	240	-	4.5	2803	49	38	-	7.8	1.32
67	0.18	1.09	27	0.66	51.5	1.7	109	168	500	-	119	380	-	6.2	3620	29	24	-		1.32
68	0.37	3.30	27	0.66	58	3.1	109	111	180	2.7	74	140	1.8	6.23	3001	33	22	33		0.87
69	0.37	1.67	27	0.66	56	1.3	109	250	570	5.5	148	420	4.6	3.53	1810	41	26	20		1.96
70	0.88	3.3	50	0.8	52	1.19	136	267	-	5.4	168	-	1.8	5.63	3199	37	-	67	9.75	2.61
71	0.88	6.87	50	0.8	45	1.95	136	128	-	1.0	12	-	0	5.70	4118	91	-	100		1.25
72	0.88	2.13	50	0.8	52	0.771	136	413	-	5.2	83	-	1.0	5.02	1683	80	-	81		4.04

A/S: Mean x 10 = 2.052, σ x 10 = 0.98

TABLE H5. EXPERIMENTAL RESULTS. DAF PILOT PLANT, PHASE 3

Treatment No.	Test	Polymer dose (mg/g)	$FeCl_3$ dose (mg/L)	A/S x 100	Flow (L/min)	Influent		Effluent		Float		Sol P red (%)	Hydr load (m/h)	Solids load ($kg/m^2 \cdot h$)
						SS (mg/L)	Sol P (mg/L)	SS (mg/L)	Sol P (mg/L)	TS (%)	TP			
1	1	1.00	25	4.06	45	2116	0.8	25	0.2	6.98	1773	75	3.24	8.54
	2	0.97	25	3.81	45	2725	0.8	39	0.2	5.50	1430	75	3.24	8.89
	3	0.84	25	2.82	45	3129	0.7	72	0.1	5.16	1579	86	3.24	10.21
	4	1.07	26	3.57	45	2463	1.2	33	1.7	5.00	1535	-	3.24	8.00
2	5	1.01	-	3.46	68	2684	0.6	35	1.0	6.68	1918	-67	4.88	13.08
	6	0.92	-	3.21	68	2936	1.3	39	1.8	7.49	2118	-38	4.88	14.36
	7	0.94	-	3.43	68	2871	1.0	81	0.2	5.84	1579	10	4.88	14.06
3	8	1.46	-	3.37	45	2860	-	30	-	6.14	1718	-	3.24	9.33
	9	1.48	-	3.37	45	2821	-	22	-	6.50	1670	-	3.24	9.18
	10	1.47	-	3.40	45	2837	-	26	-	6.69	1875	-	3.24	9.27
4	11	1.59	25	3.34	68	2627	1.8	17	-	7.18	2185	33	4.88	12.84
	12	1.35	25	2.81	68	3091	0.5	14	0.2	8.55	2624	100	4.88	15.14
	13	1.44	25	3.31	68	2912	0.6	15	0.2	6.55	1811	100	4.88	14.26
5	14	0.85	-	3.74	45	3118	-	105	-	6.06	1818	-	3.24	10.16
	15	0.91	-	4.90	45	2890	-	60	-	7.12	1758	-	3.24	9.42
	16	0.85	-	4.13	45	3114	-	71	-	6.69	1820	-	3.24	10.15
	17	0.85	-	4.26	45	3094	1.1	28	0.5	7.1	1878	98.5	3.24	10.10
6	18	0.85	25	2.56	68	3107	0.3	35	0.1	6.03	2680	98.5	4.88	15.18
	19	0.91	25	3.49	68	2895	2.0	21	0.3	6.36	2223	97.9	4.88	14.16
	20	0.89	25	3.16	68	2971	1.0	28	0.2	6.76	2544	99	4.88	14.55
7	21	1.36	26	4.30	45	3059	0.7	20	0.1	7.6	2019	86	3.24	9.96
	22	1.28	26	3.89	45	3249	0.5	101	0.2	6.2	1712	60	3.24	10.60
	23	1.67	26	5.04	45	2505	0.5	26	0.2	8.0	2225	60	3.24	8.15
	24	1.58	25	5.43	45	2655	1.8	17	0.3	7.31	1767	83	3.24	8.64

TABLE H5. EXPERIMENTAL RESULTS. DAF PILOT PLANT, PHASE 3 (Cont'd)

Treatment No.	Test	Polymer dose (mg/g)	$FeCl_3$ dose (mg/L)	A/S x 100	Flow (L/min)	Influent SS (mg/L)	Influent Sol P (mg/L)	Effluent SS (mg/L)	Effluent Sol P (mg/L)	Float TS (%)	Float TP	Sol P red (%)	Hydr load (m/h)	Solids load ($kg/m^2 \cdot h$)
8	25	1.52	-	4.06	68	2753	0.8	13	0.7	6.77	2138	12.5	4.8	13.48
	26	1.52	-	4.78	68	2757	0.8	23	0.2	7.44	1993	77.8	4.8	13.48
	27	1.66	-	3.68	68	2317	1.0	43	0.9	7.46	2845	10	4.8	12.20
	28	1.60	-	3.54	68	2619	1.0	34	1.0	7.19	2738	0	4.8	11.53
9	29	0.80	-	2.91	45	3312	-	23	-	7.37	2065	-	3.24	10.79
	30	0.86	-	2.00	45	3076	1.3	58	1.0	5.11	2280	30	3.24	10.01
	31	0.78	-	2.64	45	3385	1.7	48	1.7	6.08	1831	-	3.24	11.03
10	32	1.31	-	3.67	45	3180	-	48	2.5	6.61	1980	-	3.24	10.35
	33	1.42	-	4.83	45	2933	-	36	-	6.14	1516	-	3.24	9.57
	34	1.69	-	5.45	45	2469	-	44	-	6.57	1706	-	3.24	8.06
11	35	1.39	-	2.58	68	2999	-	49	-	6.33	2180	-	4.88	14.65
	36	1.40	-	2.73	68	2969	-	31	-	8.23	2707	-	4.88	14.50
	37	1.70	-	3.16	68	2445	2.0	116	1.8	5.63	1944	10	4.88	14.40
12	38	0.43	-	3.23	45	3049	0.4	71	0.4	5.41	1483	0	3.24	9.77
13	39	0.48	-	2.70	68	2725	1.0	390	0.8	5.76	2084	20	4.88	13.30
14	40	0.67	-	4.39	68	1983	0.8	356	0.4	5.87	1797	50	4.88	9.72
15	41	0.42	25	2.87	45	3103	0.8	38	0.2	4.64	1406	75	3.24	10.11
	42	0.45	25	3.09	45	2903	1.2	39	1.5	5.18	1557	75	3.24	9.47
16	43	1.15	-	2.07	91	2669	1.7	35	1.7	6.50	2658	0	6.50	17.38
	44	0.81	-	1.97	91	3256	1.2	53	1.1	6.25	2680	8	6.50	21.24
	45	0.77	-	1.87	91	3435	1.2	41	0.9	5.95	2545	25	6.50	22.46

APPENDIX I
ANALYSIS OF FACTORIAL DESIGN.
DAF PILOT PLANT, PHASE 3

APPENDIX I ANALYSIS OF FACTORIAL DESIGN DAF PILOT PLANT PHASE 3

Description of Design (see Davies, 1956, Chapters 7, 9, 10).

The design is a 1/2 replicate of 2^4, i.e., 2^{4-1}, with each treatment repeated at least three times; there were eight sets of treatments, and the analysis used data from 24 experiments. The response data are presented in Table H5. Note that tests 4, 17, 22, and 26 were not used in the statistical analysis.

TABLE II. VARIABLES USED IN THE FRACTIONAL FACTORIAL DESIGN

	Independent Variables			
		Levels and Sign		
Notation	Variable	Lower	Upper	Dependent Variables
a	chemical dose (mg/L)	0 -	25 +	Float TS (%)
b	influent flow (L/min)	45 -	68 +	Effluent SS (mg/L)
c	polymer dose (mg/g)	0.88 -	1.39 +	Thickening Parameter
d	A/S	0.028 -	0.041+	

Defining contrast: - ABCD

Principle block: 1, ab, ac, bc, ad, bd, cd, abcd

Design block: a, b, c, abc, d, abd, acd, bcd

Aliases		
	a: bcd	ab: cd
	b: acd	ac: bd
	c: abd	ad: bc
	d: abc	1: abcd

TABLE I2. SIGN TABLE AND RESPONSE TOTALS: FLOAT TS

	Level of Factor				
	A	B	C	D	
Treatment No.	Chemical - = 0 mg/L + = 25 mg/L	Influent Flow - = 45 L/min + = 684 L/min	Polymer - = 0.58 mg/g + = 1.37 mg/g	A/S - = 0.028 + = 0.041	Response Σ Float T S (%)
1 (a)	+	-	-	-	17.64
2 (b)	-	+	-	-	20.01
3 (c)	-	-	+	-	19.33
4 (abc)	+	+	+	-	22.28
5 (d)	-	-	-	+	19.87
6 (abd)	+	+	-	+	19.15
7 (acd)	+	-	+	+	22.91
8 (bcd)	-	+	+	+	21.42
					Σ 162.61

Calculation of effects:

Total A = 17.64 - 20.01 - 19.33 + 22.28 - 19.87 + 19.15 + 22.91 - 21.42

= 1.35

Main effect A = $\frac{1.35}{12}$ = 0.1125

TABLE 13. TOTAL EFFECTS AND ANALYSIS OF VARIANCE

(1) Comparison	(2) Total	(3) Effect = 2/12	(4) D.F.	(5) SS $2^2/24$
A	1.35	0.1125	3	0.0759
B	3.11	0.259	3	0.403
C	9.27	0.773	3	3.58
D	4.09	0.34	3	0.697
AB, - CD	-1.35	-0.1125	3	0.0759
AC, - BD	7.53	0.628	3	2.36
AD, - BC	0.19	0.016	3	0.0015
TOTAL			21	7.193

Error Variance:

An additional mean square is supplied by the variation between repeats for each set of conditions. This is obtained as a difference between

(A) the sum of the sums of squares for the $2^n - 1$ effects, and

(B) the total sum of squares of all $m \times 2^n$ individual observations.

In this case $2^n - 1 = 2^3 - 1 = 7$

$m \times 2^n = 3 \times 2^3 = 24$

(A) = 7.193

$$(B) = (6.98^2 + 5.50^2 + ... + 7.19^2) - \frac{(162.61)^2}{24} = 14.0$$

$$\therefore \text{ Error variance} = 14.0 - 7.193$$

$$= 6.807$$

$$\text{Error mean square} = \frac{\text{error variance}}{\text{d.f.}}$$

where: d.f. = d.f./cell x number of cells

= 2 x 8

= 16

$$\therefore \quad \text{Error mean square} = \frac{6.807}{16} = 0.425$$

The significance of the mean sums of squares in the analysis of variance must be tested against the error mean square by means of the F test.
In this case:

$$\alpha = 0.05$$
$$\upsilon_1 = 3$$
$$\upsilon_2 = 16$$

then, $F_{0.05;\,3,16} = 3.24$

Thus, the minimum mean square value for significance at 5% is

$$3.24 \times 0.425 = 1.377$$

Both main effect C (polymer addition) and interaction AC or - BD are significant. Since the levels of d were questionable it is suspected that the relevant effects are C and AC.

TABLE 14. INTERACTION OF POLYMER AND CHEMICAL EFFECT ON FLOAT TS

		C: -	C: +
		Low Polymer	High Polymer
A: -	No Chemical	6.64	6.79
A: +	With Chemical	6.13	7.53

Conclusion:

Best results are obtained with chemical and high polymer. At low polymer dose, chemical addition has a deleterious effect.

B) Effluent Observations, Response Totals

C) Thickening Parameter, Response Totals

The sign table is the same as for part A, and the results for B) and C) are tabulated below.

TABLE I5. RESPONSE TOTALS OF EFFLUENT SS AND TP

Treatment No.	Response Σ Effluent SS (mg/L)	Response Σ TP
1 (a)	136	4782
2 (b)	155	5616
3 (c)	78	5262
4 (abc)	46	6621
5 (d)	236	5397
6 (abd)	84	7446
7 (acd)	63	6012
8 (bcd)	90	7722
	Σ888	Σ48855

TABLE I6. SUM OF SQUARES FOR ANALYSIS OF VARIANCE. EFFLUENT AND TP

Comparison	Effluent Sum of Squares	TP Sum of Squares
A	2204	62 208
B	793.5	1 476 096
C	4648	235 224
D	140.2	768 984
AB, - CD	0	14 701
AC, - BD	522.67	102 182
AD, - BC	682.67	1 442
	8991	2 598 629

TABLE 17. SIGNIFICANT EFFECTS ON EFFLUENT AND TP

	Effluent	TP
Error Main Square	263	68811
Min. SS for Significance	852	222948
Significant Comparisons	A;C	B;D (C too close)

TABLE 18. INTERACTION OF POLYMER AND CHEMICAL EFFECT ON EFFLUENT SS

			C -	C +
			Low Polymer	High Polymer
A	-	No Chemical	65	28
	+	With Chemical	36	18

Conclusion:

Both chemical and polymer addition independently improve the effluent; the optimum effluent is obtained when polymer and chemical are added. Interaction in this case is minimal.

TABLE 19. INTERACTION OF INFLOW AND A/S EFFECT ON TP

			D -	D +
			Low A/S	High A/S
A	-	Low Flow	1674	1901
	+	High Flow	2039	2528

Conclusion:

Both increasing flow and increasing A/S independently cause the value of the TP to rise; the optimum TP is at high flow and high A/S. Interaction in this case is minimal.

APPENDIX J
SOLIDS BALANCE CALCULATIONS
DAF PILOT PLANT, PHASE 3

APPENDIX J SOLIDS BALANCE CALCULATIONS. DAF PILOT PLANT, PHASE 3

Test	Influent		Mass flow (g/min)	Skimmer		Float		Flow/min on time (L/min)	Mass Flow (g/min)	Mass flow /min on time (g/min)	Solids balance error (%)
	Flow (L/min)	SS (mg/L)		On (min)	Off (min)	TS (mg/L)	Flow (L/min)				
11	68.2	2627	179	10	2	71809	2.3	2.76	165	198	-3.4
12	68.2	3091	211	10	2	85498	2.4	2.85	205	246	-2.8
13	68.2	2912	198	10	2	65460	2.7	3.2	177	212	-10.6
17	68.2	3094	211	10	2	70804	1.1	1.32	78	94	
18	68.2	3107	212	10	2	60268	2.9	3.5	175	211	-17.5
19	45.5	2655	121	6	6	73133	1.8	3.6	132	264	+9.1
20	68.2	2971	203	10	2	67607	2.9	3.5	196	235	-3.4
21	45.5	3059	139	6	6	75935	1.7	3.4	129	258	-7.2
22	45.5	3249	148	6	6	61772	2.3	4.6	142	284	-4.0
24	68.2	2895	197	10	2	63577	3.1	3.7	197	236	0
25	68.2	2753	188	10	2	67668	2.3	2.76	156	187	-17.0
26	68.2	2757	188	10	2	74362	3.0	3.6	223	268	+15.7
27	68.2	2517	172	10	2	74601	2.3	2.76	172	206	0
28	68.2	2619	179	10	2	71867	1.8	2.2	129	155	-27.9
31	45.5	3385	154	8	2	60812	3.8	4.75	231	289	+33.3
38	45.5	3049	139	6	5	54098	2.1	3.85	117	208	-15.8
39	68.2	2725	185	10	2	57579	2.3	2.76	132	158	-28.6
41	45.5	3103	141	6	6	46383	1.06	2.1	49	98	
43	90.9	2669	243	Continuous		65270	6.8	6.8	444	444	+45.3
44	90.9	3256	296	Continuous		62522	4.8	4.8	300	300	+1.4
45	90.9	3435	312	Continuous		59487	5.6	5.6	333	333	+6.3
										mean	-1.6%
										σ	19.6

APPENDIX K
ESTIMATED COSTS

APPENDIX K ESTIMATED COSTS

The factors on which the estimated costs are based are, outlined below:

K1. Design Criteria

(a) Flotation of Mixed Liquor and Raw Sewage

Flotation units are sized on the basis of pilot plant performance (see Table 38) which indicated acceptable hydraulic loads as follows:

	ML (EA) 4600 mg/L	RS 220 mg/L	ML (AS) 2900 mg/L
Hydraulic Load (m/h)	2.27	6.50	4.88

(b) Sedimentation of Mixed Liquor and Raw Sewage

Settling tanks are sized in accordance with the current practice of the Ontario Ministry of the Environment.

	ML (EA) 4600 mg/L	RS 220 mg/L	ML (AS) 2900 mg/L
Overflow Rate (m/h)	0.61	0.82	0.82

(c) Flotation Thickening of Settled Sludge

Sizing of flotation thickeners for concentrating secondary sludge from a conventional activated sludge plant assumes a BOD of 0.08 kg/person.d, 30 percent BOD removal in the primaries, and a sludge growth factor of 0.65 (SS/BOD removed). Endogenous respiration is neglected. Operating times of 8, 16 and 24 hours per day for 4500, 45 500 and 227 000 m^3/d plants respectively are assumed for estimating power costs for DAF units.

The sizing of flotation thickeners for concentrating settled secondary sludge from an extended aeration plant assumes that the net sludge production will be the same

as for conventional activated sludge, i.e., that the extra BOD load to the aeration tanks, when no primaries are used, is offset by the sludge loss from endogenous respiration.

K2. Labour Requirements

The daily man-hours to operate the selected equipment, shown in Table K1, are estimated using information from plant operators and equipment suppliers.

TABLE K1 SUMMARY OF LABOUR REQUIREMENTS FOR FLOTATION AND FOR SETTLING

	Units and Man-Hours per Day		
	4500 m^3/d	45 500 m^3/d	227 000 m^3/d
ML Flotation (EA)	2 - 37 m^2 -	10 - 74 m^2 24	24 - 186 m^2 54
RS Flotation	2 - 19 m^2 3	4 - 74 m^2 16	8 - 196 m^2 41
ML Flotation (AS)	2 - 19 m^2 3	5 - 74 m^2 16	10 - 186 m^2 41
Flotation Thickening (EA or AS)	1 - 5 m^2 1 1/2	2 - 14 m^2 3	2 - 37 m^2 5
Final Settling (EA)	2-6.1m x 24m x 3.7m 1 1/4	10-6.1m x 50m x 3.7m 4	20-12m x 62m x 3.7m 12
Primary Settling	2-5.4m x 21m x 3m 1 1/4	8-6.1m x 50m x 3m 3	16-12m x 59m x 3m 10
Final Settling (AS)	2-5.4m x 21m x 3.7m 1 1/4	8-6.1m x 50m x 3.7m 3	16-12m x 57m x 3.7m 10

K3. Unit Costs

The unit costs for the items noted are typical of prices in effect in southern Ontario in October 1977. Where two values are given the higher one applies to the smallest project.

Labour $7.00 per hour

Power	3.1¢/kWh	
Polymer	$3.52 kg (Percol 728, Percol 757)	
Ferric Chloride	$18.79/100 kg (100% basis)	
Maintenance	1% of equipment cost	
Excavation	$3.27 to $3.92/$m^3$	
Concrete:	$222 to $262/$m^3$	

DAF Units:				
	5 m^2	(50 ft^2)	$ 50 000	(including tank)
	14 m^2	(150 ft^2)	70 000	(including tank)
	23 m^2	(250 ft^2)	90 000	(including tank)
	37 m^2	(400 ft^2)	130 000	(including tank)
	74 m^2	(800 ft^2)*	130 000	(excluding tank)
	186 m^2	(2000 ft^2)*	200 000	(excluding tank)

* Costs for poured in place concrete tanks are covered in the building costs.

Controls, Chemical Feed Systems:

- included with prefabricated steel units
- extra with concrete tanks

Buildings: $3.27 to $4.58/$m^3$ (structure only)
$4.25 to $5.89/$m^3$ (including mechanical and electrical)

K4. Sizing DAF Units

DAF units for primary and final clarification are sized on the basis of the hydraulic loads at which the units were continuously operated (see Appendix K1).

DAF units for flotation thickening are sized on the basis of the assumptions noted in Appendix K1 and the manufacturer's recommendations for solids loading, normally 9.8 kg/m^2·h.

The 45 500 m^3/d conventional activated sludge plant will illustrate the procedure.

a) Final Clarification

Hydraulic load = 4.88 m/h = 117 m/d

$$\text{Area} = \frac{45\,500}{117} = 388\ m^2$$

Use: five 74-m^2 units in concrete tanks.

b) Flotation Thickening

Waste sludge = 100 000 x 0.055 x 0.65 = 3600 kg/d

Solids load = 9.8 kg/m^2•h = 235 kg/m^2/•d

Operating time = 112 h per 168-h week

$$\text{Area} = \frac{3600}{235} \times \frac{168}{112} = 23 \text{ m}^2$$

Use: two 14-m^2 prefabricated steel units.

K5. Flotation Power Requirements

Estimated values adapted from data sheets provided by Komline-Sanderson Engineering Corporation are shown in Table K2.

K6. Flotation and Sedimentation Costs (45 500 m^3/d Activated Sludge Plant)

The following estimate is shown in detail to illustrate how construction costs for three sizes of plants were determined using the preceding information.

Work not Included

Prices estimated are construction costs excluding land. There is no allowance for engineering and legal fees, administrative costs or borrowing charges which could amount to 20 percent of the construction cost. Similarly, a proportionate share of the plant yard work, bonds, insurance or contingency (which would increase the costs shown by 10 to 15 percent) has not been added. Feed and effluent pumps for DAF flotation (or flotation thickening) and the raw sludge or waste activated pumps (for primary or final settling) are also not included in the estimate.

1) Flotation of Mixed Liquor (2900 mg/L)

Capital Cost

(a)	Flotation Units (74 m^2)	
	Supply 5 @ $130 000	$ 650 000
	Installation 10%	65 000
(b)	Building (1490 m^2)	
	Excavation and backfill	
	Architectural finishes	

TABLE K2 SUMMARY OF POWER REQUIREMENTS FOR FLOTATION

	Power (kWh)			
	EA	RS	AS	FT
19 m^2 Unit				
Recirculation pump	22	21	31	22
Reaeration pump	4.5	4.5	6	3.7
Collectors	0.6	0.6	0.6	0.6
Polymer mixer and pump	1.1	1.1	1.1	1.1
Air compressor	1.1	0.6	0.6	2.2
TOTAL	29	28	39	30
37 m^2 Unit				
Recirculation pump	42	42	63	37
Reaeration pump	9	9	12	7
Collectors	1.3	1.3	1.3	1.3
Polymer mixer and pump	1.1	1.1	1.1	1.1
Air compressor	1.9	.7	.7	3.7
TOTAL	55	54	78	50
74 m^2 Unit				
Recirculation pump	75	75	119	56
Reaeration pump	19	19	30	15
Collectors	2.2	2.2	2.2	2.2
Polymer mixer and pump	1.1	1.1	1.1	1.1
Air compressor	3.7	1.5	1.5	7
TOTAL	101	99	154	81
186 m^2 Unit				
Recirculation pump	224	224	336	130
Reaeration pump	56	56	84	37
Collectors	3.7	3.7	3.7	3.7
Polymer mixer and pump	1.5	1.5	1.5	1.5
Air compressor	11	4.5	4.5	22
TOTAL	296	290	430	194

		Roof		
		Concrete (including DAF tanks)		
		Mansory, structural steel		
		Cranes, monorails, lifts		$1 200 000
	(c)	Mechanical and Electrical		
		Heating and ventilating		
		Pumping and valves		
		Plumbing		
		Wiring and substation		600 000
	(d)	Polymer Feed System (dry & liquid)		
		Supply and installation		273 000
	(e)	Automatic Controls		190 000
			Total	$2 978 000

Operating Cost

(a)	Power:	154 kW x 5 x $268/kW/yr		206 000
(b)	Labour:	16 h x 365 x $7/h		41 000
(c)	Maintenance:	1% DAF cost		6 500
(d)	Polymer:	1.45 mg/g @ $3.52/kg		237 000
(e)	$FeCl_3$:	25 mg/L @ $18.79/100 kg		228 000
			Total	$ 718 500

2) Final Settling (6.1 m x 47.5 m x 3.7 m)

Capital Cost (8 tanks)

(a)	Excavation:		
	Sheeting, storing, dewatering		$ 36 000
(b)	Concrete:		
	Forming and placing		
	Reinforcing steel		
	Weirs, troughs, network		$ 333 000
(c)	Equipment:		
	Supply and installation		
	Collectors, cross collectors		
	Motors, drives, skimmers		$ 656 000
		Total	$1 025 000

Operating Cost

(a)	Power:	1.1 kW x 8 x $268/kW/yr		2 400
(b)	Labour:	3 h x 365 x $7/h		7 700
(c)	Maintenance:	1% capital cost		10 000
			Total	$ 20 100

3) Flotation Thickening

Capital Cost

(a)	Flotation Units (14 m^2)		
	Supply two 14-m^2 each @ $70 000		$ 140 000
(b)	Holding Tank (4.6 m x 7.6 m x 4.6 m)		
	Excavation		
	Concrete and reinforcing		
	Aeration system		19 000
(c)	Building (186 m^2)		
	Architectural, structural		
	Mechanical and electrical		$ 249 000
		Total	$ 422 000

Operating Cost

(a)	Power:	26 kW x $\frac{16}{24}$ h/d x $268/kW/yr	$4 700	
(b)	Labour:	3 h x 365 x $7/h		7 700
(c)	Maintenance:	1% DAF cost		1 400
(d)	Polymer:	(1.25 mg/g)		5 800
			Total	$ 19 600

SUMMARY OF COSTS

Estimated costs summarized below are for the units indicated thus where:

P = Primary settling

A = Aeration

S = Secondary settling

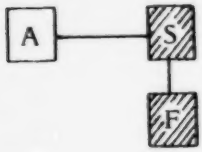
F = Flotation

Alternatives Considered

1. Extended Aeration (4600 mg/L)

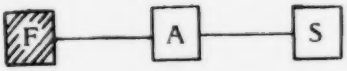
(a)

(b)

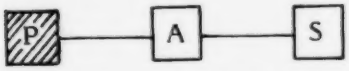


2. Raw Sewage (220 mg/L)

(a)

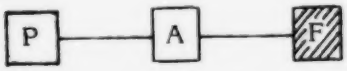


(b)



3. Activated Sludge (2900 mg/L)

(a)



(b)

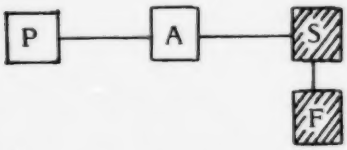


TABLE K3 SUMMARY OF COSTS IN DOLLARS

	4500 m^3/d	45 500 m^3/d	227 000 m^3/d
Capital Costs			
1 (a) Flotation (EA)	670 000	5 484 000	22 680 000
(b) Secondary Settling	172 000	1 313 000	5 752 000
Flotation Thickening	121 000	422 000	676 000
	293 000	1 735 000	6 428 000
Operating Costs			
1 (a) Flotation (EA)	45 400	345 000	2 100 000
Polymer	24 200	242 000	1 210 000
	69 600	587 000	3 310 000
(b) Secondary Settling	5 800	28 000	119 000
Flotation Thickening	4 200	13 300	29 000
Polymer	600	5 800	29 200
	10 600	47 100	177 200
Capital Costs			
2 (a) Flotation (RS)	390 000	2 437 000	9 330 000
(b) Primary Settling	125 000	965 000	4 260 000
Operating Costs			
2 (a) Flotation (RS)	23 300	181 000	901 000
Polymer	2 600	26 000	130 000
	25 900	207 000	1 031 000
(b) Primary Settling	4 500	19 700	82 600
Polymer	2 600	26 000	130 000
	7 100	45 700	212 600
Capital Costs			
3 (a) Flotation (AS)	390 000	2 978 000	11 000 000
(b) Secondary Settling	134 000	1 025 000	4 500 000
Flotation Thickening	121 000	422 000	676 000
	255 000	1 447 000	5 176 000
Operating Costs			
3 (a) Flotation (AS)	21 000	253 500	1 275 000
Polymer	23 700	273 000	1 185 000
Ferric Chloride	22 800	228 000	1 140 000
	68 200	718 500	3 600 000
(b) Secondary Settling	5 100	20 300	104 000
Flotation Thickening	4 200	13 300	29 000
Polymer	600	5 800	29 200
	9 900	39 400	162 200